POWER SYSTEMS -I

B. Tech (II Year, II Semester)

Electrical & Electronics Engineering

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PREAMBLE

Electrical Power plays significant role in day to day life of entire mankind. The aim of this course is to allow the student to understand the concepts of the Generation and Distribution of power along with economic aspects.

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LEARNING OBJECTIVES AND OUTCOMES

1. **Objective**: **To study** the principle of operation and function of different components of a Thermal Power Stations.

   Outcome: Students are **able to identify** the different components of TPS

2. **Objective**: **To study** the principle of operation and function of different components of a Nuclear Power Stations.

   Outcome: Students are **able to identify** the different components of NPS

3. **Objective**: **To study** the Concepts of DC and AC Distribution System along with Voltage Drop Calculations.

   Outcome: Students are **able to distinguish** between DC and AC Distribution System and also estimate voltage drops of distribution system

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LEARNING OBJECTIVES AND OUTCOMES

4. **Objective**: **To study** the construction details, principle of operation and function of different components of an Air and Gas Insulated Substations.

   Outcome: Students are **able to identify** different components of an Air and Gas Insulated Substations.

5. **Objective**: **To study** the constructional details different types of Cables.

   Outcome: Students are **able to identify** single core and multi core Cables with different insulating materials.

6. **Objective**: **To study** the concepts of different types of Load Curves and types Tariff applicable to consumers.

   Outcome: Students are **able to analyze** the different Economic Factors of power generation and Tariff.

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IMPORTANCE OF ELECTRICITY

Introduction

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IMPORTANCE OF ELECTRICAL ENERGY

- Economy of a Country depends on the Electrical Energy.
  - Poor Electricity - Poor Economy
  - Sufficient Electricity - Very Good Economy
- Availability of sufficient energy and its proper use can result highest of standard of living.
- Interesting Fact: Asia's population – more than half of the world's
  Asia's energy consumption – 15 to 20% of the world
- More than half of the world's energy consumed – North America and Western Europe.

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WORLD ELECTRIC ENERGY PRODUCTION

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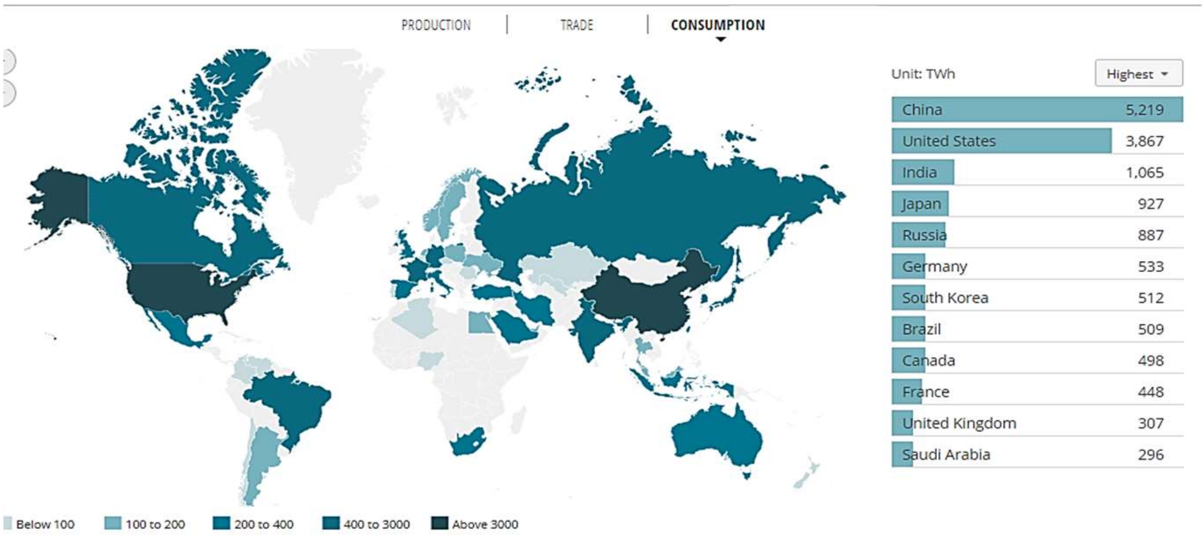
WORLD ELECTRIC ENERGY PRODUCTION



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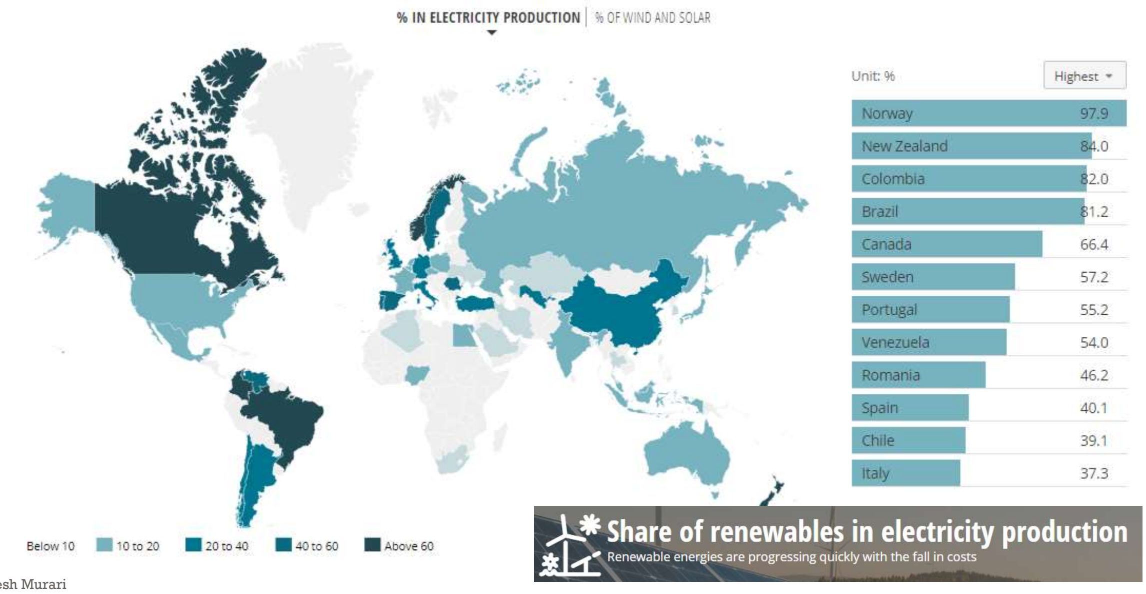
WORLD ELECTRIC ENERGY PRODUCTION



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WORLD ENERGY CONSUMPTION

Rank	Area	Population
1	Russia	China
2	Canada	**India**
3	USA	USA
4	China	Indonesia
5	Brazil	Brazil
6	Australia	Pakistan
7	**India**	Bangladesh
8	Argentina	Nigeria
9	Kazakhstan	Russia
10	Sudan	Japan

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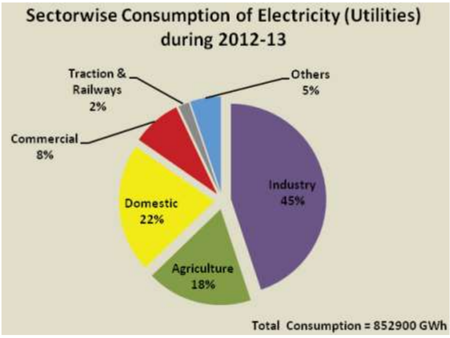
INDIA ENERGY GROWTH

(Giga Watt hour) = (10^6 x Kilo Watt hour)

Year	Utilities				Non-Utilities	Grand
	Thermal *	Hydro	Nuclear	Total		Total
1	2	3	4	5 = 2 to 4	7	9=5+8
2005-06	505,001	101,494	17,324	623,819	73,640	697,459
2006-07	538,350	113,502	18,802	670,654	81,800	752,454
2007-08	585,282	120,387	16,957	722,626	90,477	813,102
2008-09	617,832	113,081	14,713	745,626	95,905	842,531
2009-10	670,965	106,680	18,636	796,281	109,693	905,974
2010-11	704,323	114,257	26,266	844,846	114,224	959,070
2011-12	708,427	130,511	32,287	922,451	128,172	1,051,375
2012-13(p)	817,225	113,626	32,871	963,722	148,000	1,111,722
Growth rate of 2012-13 over 2011-12(%)	0.58	14.23	22.92	9.19	12.21	9.62
CAGR 2005-06 to 2012-13(%)	6.20	1.42	8.34	5.59	9.12	6.00



	Coal	Oil	Gas	Nuclear	Renewable	others	Total
World	41%	5%	21%	13%	16%	3%	100%
India	84.8%			3.7%	11.5%	-	100%

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SOURCES OF POWER GENERATION

- Conventional Energy Sources (Thermal)
  1. Coal
  2. Gas
  3. Oil
  4. Nuclear
- Non-Conventional (Renewable) Energy Sources
  1. Hydro
  2. Solar
  3. Wind
  4. Tidal
  5. Wave
  6. Ocean Thermal Energy Conversion
  7. Bio-Mass

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13 THERMAL POWER STATION

UNIT-I

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THERMAL POWER STATION (TPS)

- Objective:

To study the principle of operation and function of different components of the Thermal Power Station

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TPS: LIST OF TOPICS

- Selection of Site
- General Layout of a thermal power plant,
  - Paths showing the
    - Coal,
    - Steam,
    - Water,
    - Air,
    - Ash
    - Flue Gases,
    - Coal handling system and
    - Ash Handling System
- Description of Components:
  - Boiler Furnace
  - Boilers
  - Super-heater
  - Economizer
  - Steam Turbine
    - Impulse and
    - Reaction
  - Alternator/Generator
  - Condenser
  - Feed Water Circuit
  - Cooling Tower
  - Chimney

THERMAL POWER STATION: SITE SELECTION

- Supply of Fuel
- Ash Disposal Facility
- Availability of Water
- Land Requirements
- Transportation Facility

CONSERVATION OF ENERGY

Fuel Combustion
Chemical Energy

Furnace
Thermal Energy

Turbine
Mechanical Energy

Generator
Electrical Energy

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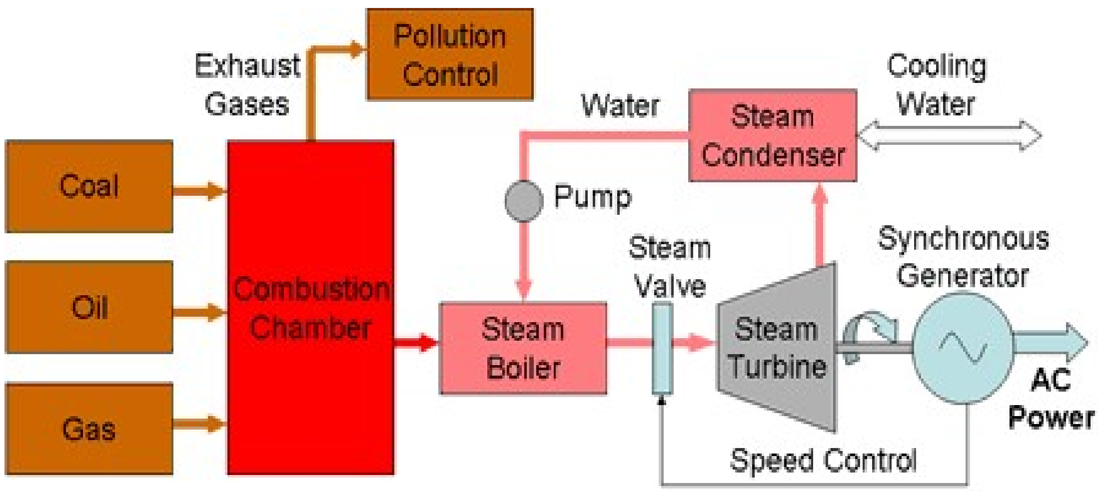
TPS WORKING PRINCIPLE



Fossil Fuel Powered Steam Turbine Electricity Generation

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TPS: TYPES

- Co-Generation (CHP-Combined Heat & Power)
- Captive Power Plant or Industrial PP
- Central Power Plants (For Different Consumers)

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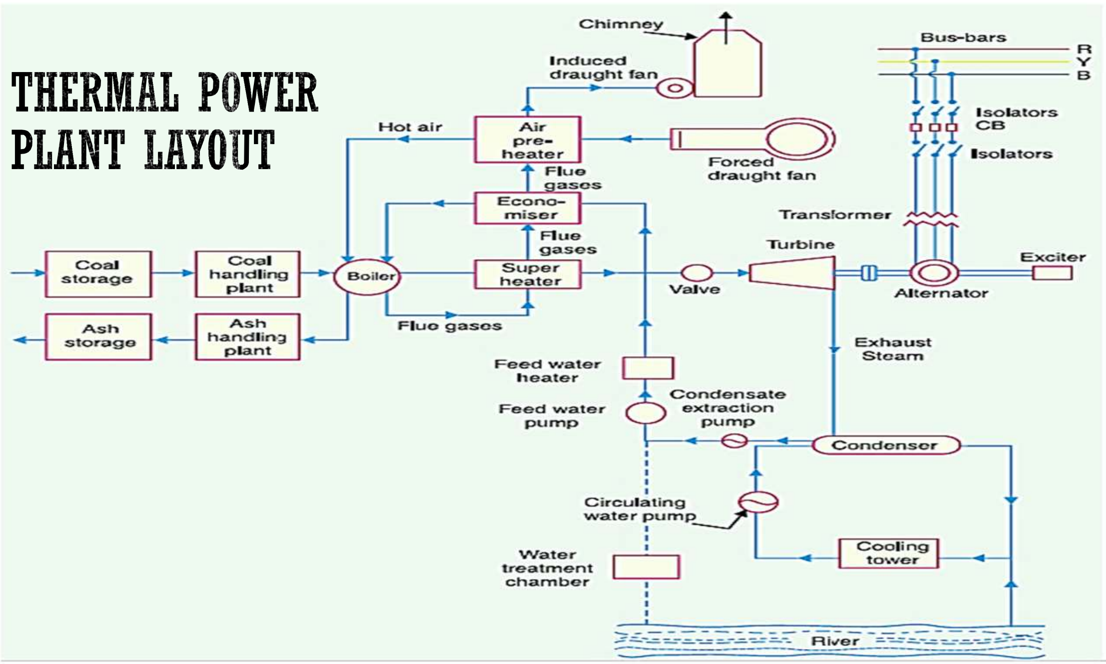

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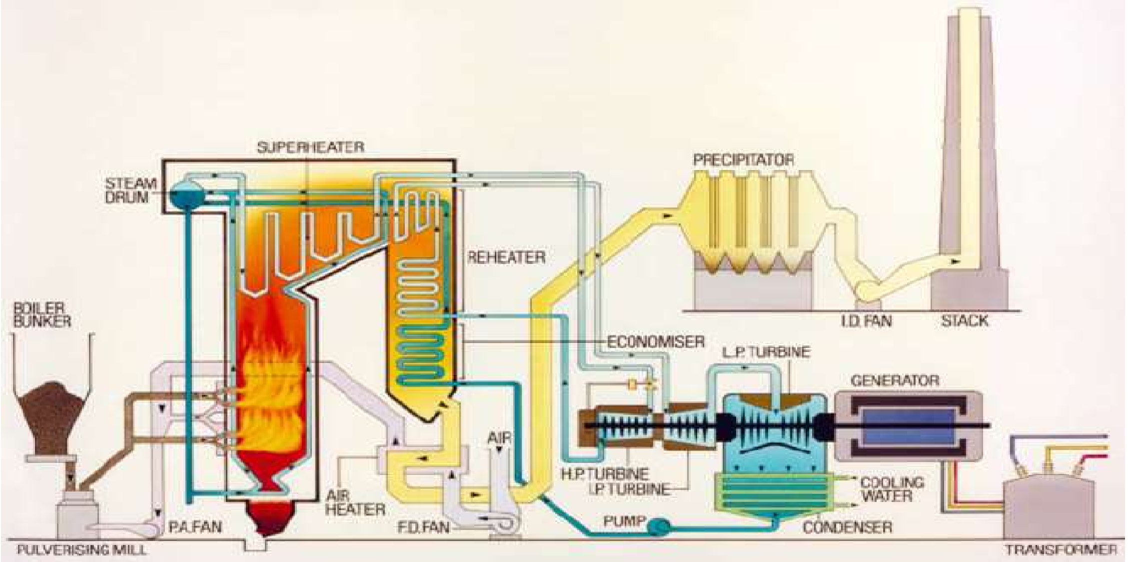
TPS WORKING



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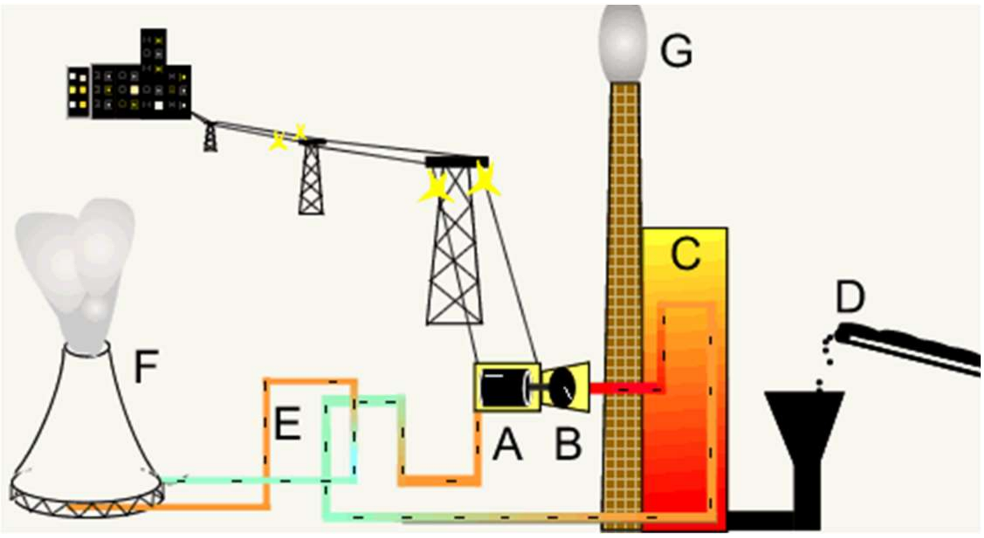
TPS WORKING



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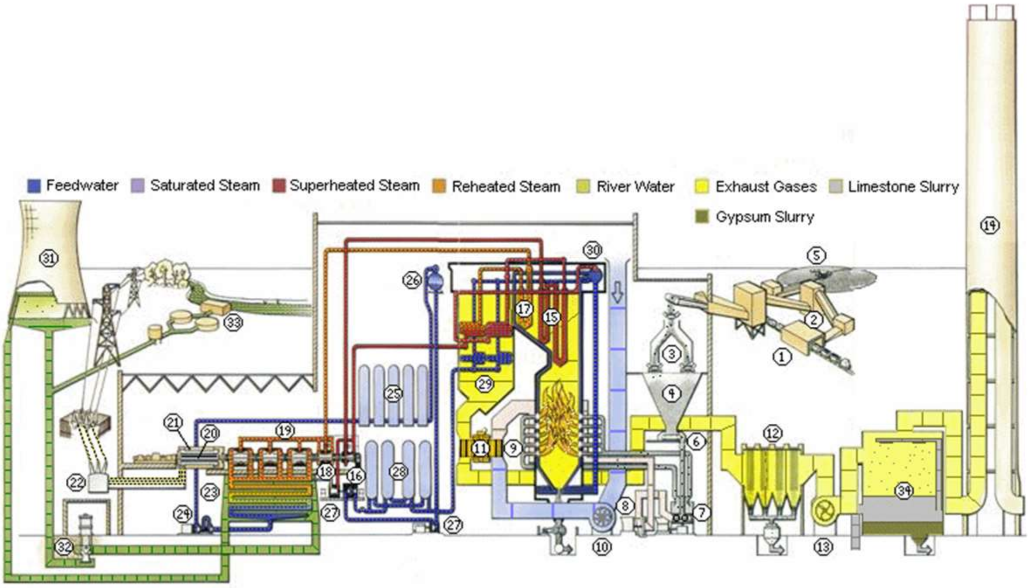
TPS WORKING



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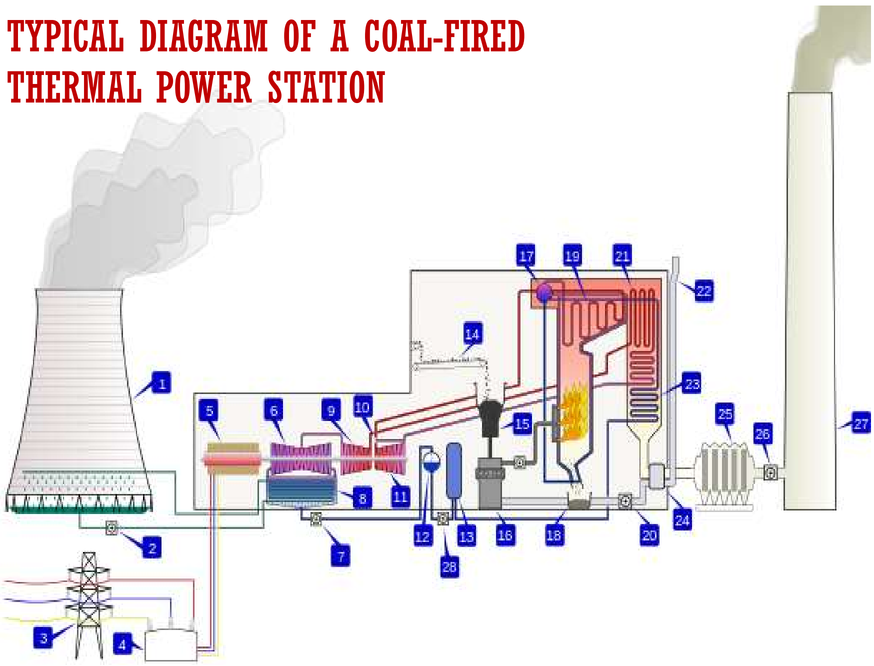
TYPICAL DIAGRAM OF A COAL-FIRED THERMAL POWER STATION



1. Cooling Tower
2. Cooling Water Pump
3. Transmission Line (3-phase)
4. Step-up Transformer (3-phase)
5. Electrical Generator (3-phase)
6. Low Pressure Steam Turbine
7. Condensate Pump
8. Surface Condenser
9. Intermediate Pressure Steam Turbine
10. Steam Control Valve
11. High Pressure Steam Turbine
12. Deaerator
13. Feed Water Heater
14. Coal Conveyor
15. Coal Hopper
16. Coal Pulveriser
17. Boiler Steam Drum
18. Bottom Ash Hopper
19. Super Heater
20. Forced Draught (Draft) Fan
21. Re-Heater
22. Combustion Air Intake
23. Economiser
24. Air Preheater
25. Precipitator (ESP)
26. Induced Draught (Draft) Fan
27. Flue Gas Stack

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COMPONENTS OF TPS

- Coal Handling Plant
- Ash Handling Plant
- Steam Generating Plant
  - Boiler
  - Economizer
  - Super Heater
- Steam Turbine
- Alternator/ Generator
- Feed Water Circuit
- Cooling Water Circuit
- Chimney

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26 COAL HANDLING PLANT

- Types of Coal
- Coal Analysis
- Coal Handling Plant (Layout)
- Coal Handling Equipment

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TYPES OF COAL

- Based on Heat Value
  - Peat: First stage of formation, Low Grade, Calorific Value <2,600 kcal/kg
  - Lignite: Brown Coal, moisture 40-50%, <4,000kcal/kg
    - Germany, Poland Russia, USA, Canada, India Australia
  - Sub-Bituminous: moisture 20-40%, 4,000-5,800 kcal/kg
  - Bituminous: moisture 8-20%, 5,800-8,000 kcal/kg
    - Carbon:>70%, Ash: 7%, Sulphur:1%
    - USA, Canada, Russia, Australia
  - Anthracite: moisture <8%, 7,800-8,500 kcal/kg, Best Coal (Fully formed)Carbon: 85%, Ash: <7%, Sulphur:0.6-0.8%
    - Russia, China, Ukraine, North Korea, Vietnam, Pennsylvania-USA, Canada

Anthracite mine in Pennsylvania, accidentally caught fire 1962 and burning ever since

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TYPES OF COAL

- Peat: 4,500 per ton
- Lignite: 5,500 per ton
- Bituminous: 11,500 per ton
- Anthracite: 13,000 per ton




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COAL ANALYSIS

- To find the commercial value of coal two tests are performed:
  - Proximate Analysis: To determine the amount of fixed carbon, volatile matters, moisture, and ash within the coal sample.

Constituents	%
Moisture	3-30
Volatile Mater	3-50
Ash	2-30
Fixed Carbon	16-92

  - Ultimate Analysis: to determine the constituent of coal, but rather in a form of its basic chemical elements.

Constituents	%
Carbon	50-95
Hydrogen	1-5.5
Oxygen	2-40
Sulpher	0.5-3
Nitrogen	0.5-7
Ash	2-30

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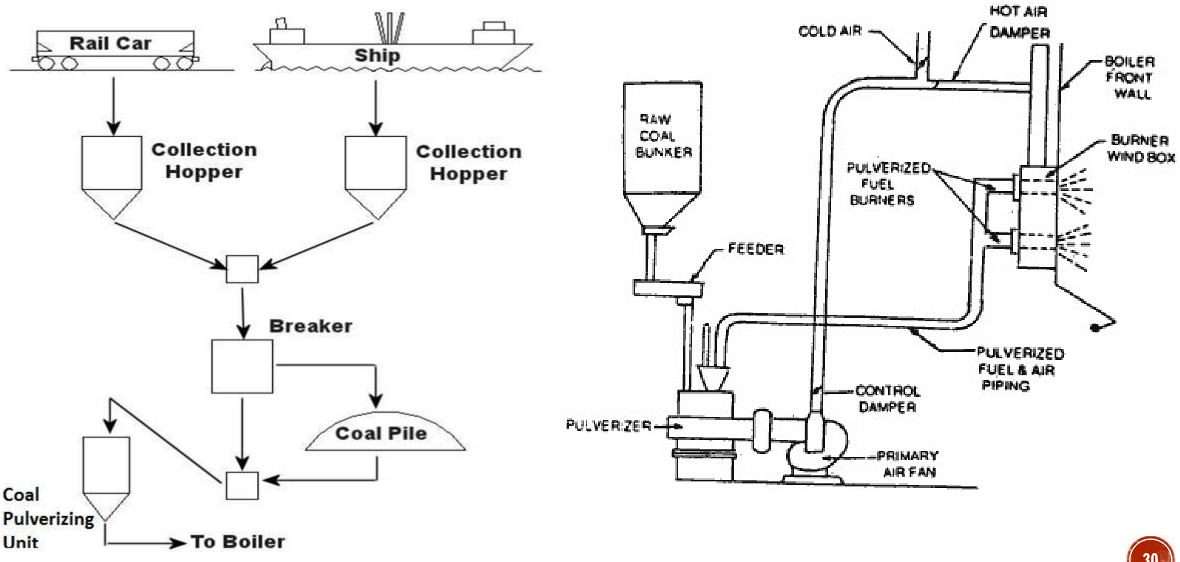
COAL HANDLING PLANT



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COAL HANDLING PLANT EQUIPMENT

- Equipment used (based on Stages of Coal Handling)
  1. Unloading: Cranes, Buckets, Unloading Towers, Rotary Car Dumpers, Car Shakers, Portable Conveyers, etc.
  2. Preparing: Crushers, Sizers, & Driers, Breakers
     - (To pulverize coal in order to increase its surface exposer, thus promoting rapid combustion without using large quantities of excess ash)
  3. Transfer: Skip Hoist Bucket Elevators, Belt Conveyors, Flight Conveyers, Grab Buckets, etc.
  4. Out Door Storage: Conveyers, Scrapers, Bulldozers, Trams, Cranes
  5. Covered Storage: Bins, Bunkers, Silos, Indicators, Alarms, Gates, etc.
  6. In-plant Handling: Belt Conveyers, Screw Conveyers, Flight Conveyers
  7. Weighing Equipment: Scales, Coal meters, & Samplers
  8. Firing Equipment

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ASH HANDLING PLANT

- Problem of Ash & Handling Difficulty
- Ash Handling Equipment
- Removal of Dust/ Ash
- Electrostatic Precipitator
- Ash volumes & Properties
- Ash handling system
- Ash Disposal

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PROBLEMS WITH ASH

- Ash from TPS is a great nuisance for
  - The designers of the plant
  - Operating staff
  - Residential areas around the plant
- Total ash content for a large TPS depends on the type of coal used.
  - Ranges from 10-50% of the coal used
  - Indian Coal – Ash content is 20-50%
  - A modern 2000MW TPS produces 5000 tons ash every day.

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ASH HANDLING DIFFICULTIES

- Ash Handling Operations
  - Removal of the ash from the furnace ash hoppers
  - Transfer of this ash to the fill or storage yard and
  - Disposal of stored ash
- Difficulties experienced in handling and disposal of ash:
  - The ash coming out of the furnace is very hot
  - Is dusty and so irritating and annoying in handling
  - Is abrasive and wears out the containers
  - Produces poisonous gases and corrosive acids when mixed with water
  - Forms clinkers by fusing together in lumps

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ASH HANDLING PLANT REQUIREMENTS

- Chief requirements of a good ash handling plant are:
  - Capability to operate with minimum attention and handle large clinkers as well as dust and soot.
  - Minimum operation and maintenance charges
  - Adequate capacity to deal with the ultimate plant capacity
  - Speedy disposal of ash
  - Ability of handling both dry and minimum dust menace.

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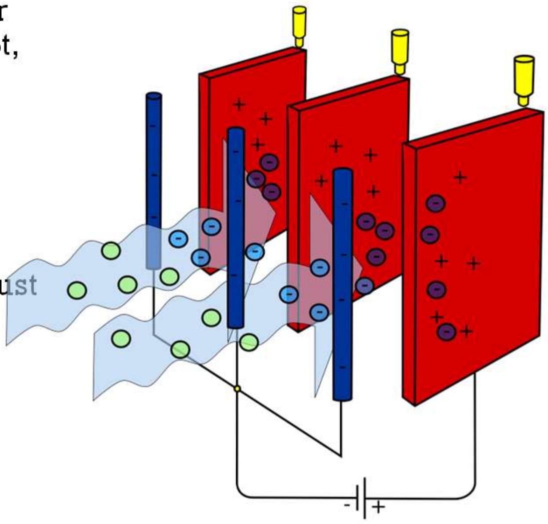
REMOVAL OF DUST/ ASH

- The exhaust gases leaving the boiler contain suspension-smoke, dust, soot, fly-ash, or carbon.
- 60 to 80 percent of the total ash produced in the furnace escapes through the chimney.
- Removal of this dust/ ash is very important. This can be done using dust collectors.
- There are various types of dust collectors, to filter dust from the flue gases.
- Electrostatic Precipitator is the most efficient & widely used.



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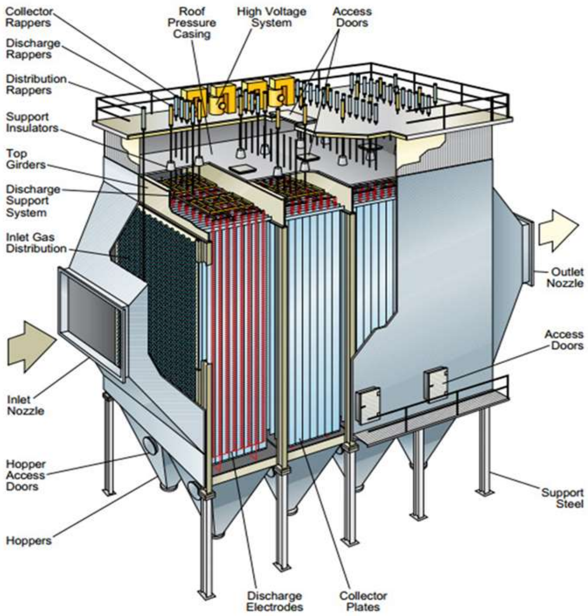
ELECTROSTATIC PRECIPITATOR

- Main Components of ESP:
  - Casing
  - Hopper
  - Collecting System
  - Emitting System
  - Rapping Mechanism for collecting system
  - Rapping mechanism for emitting system
  - Insulator Housing
  - High Voltage Rectifier along with controls
- The efficiency of the ESP is up to 99.5%



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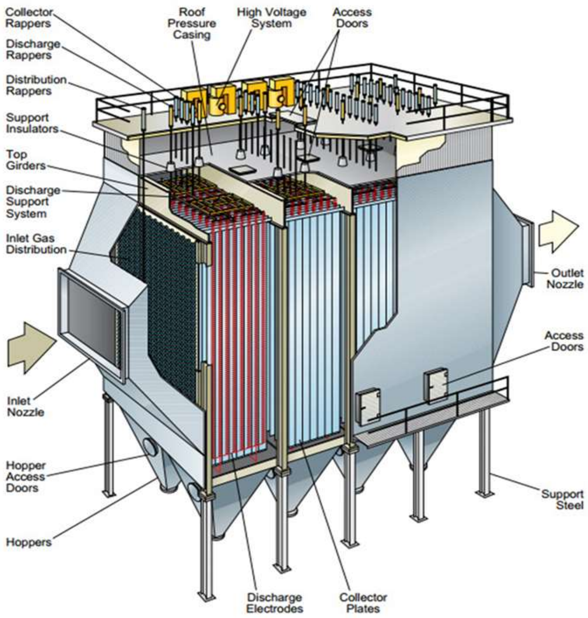
ELECTROSTATIC PRECIPITATOR

- Advantages:
  - It can remove dust particles as small as 0.01 microns in size
  - The draught loss is as small as 1.5cm hence the rating of ID fan required is reduced
  - The operation is simpler
  - The dust collected in dry form and can be removed either dry or wet.
- Disadvantage:
  - Relatively costlier.



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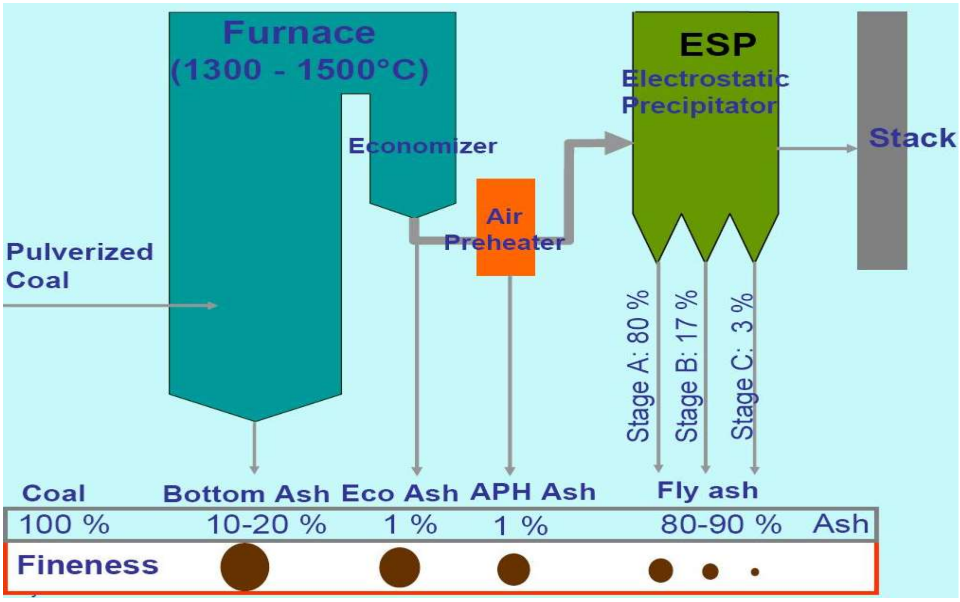
ASH VOLUMES AND PROPERTIES

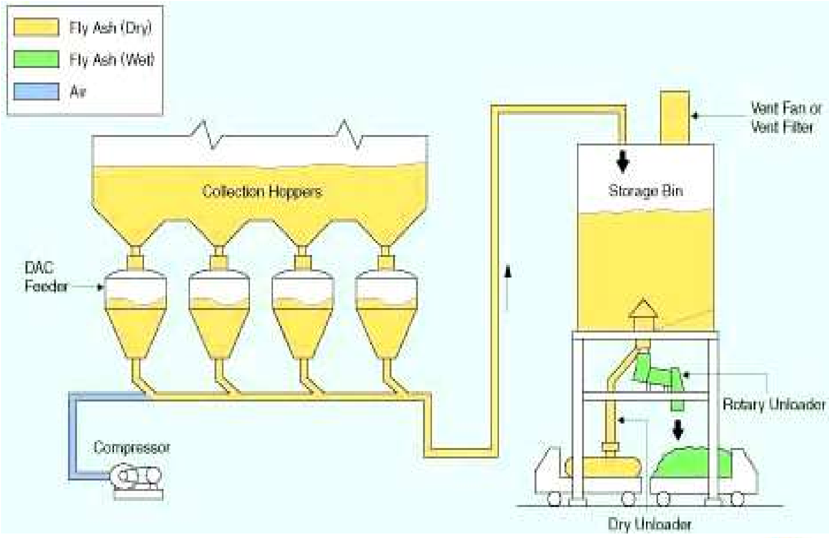


ASH HANDLING SYSTEM

- Ash Handling Systems
  - Belt Conveyor System: Hot ash from furnace is made to fall over a belt conveyer through water seal to cool it and dumps in storage. Suitable for small plants
  - Pneumatic System: Air is employed as the medium for driving ash through a pipe over long distance. It's a clean & dust free system. But noisy, frequent maintenance.
  - Hydraulic System: A stream of water carries ash along with it in a closed channel and disposes it storage site. Popular method due to its simplicity, ability to handle large amount of dust, clean & low cost. Suitable for large plants.
  - Steam Jet System: Steam is passed through a pipe at high speed which carries dry ash from the furnace hoppers. Noisy, greater wear of pipes.

ASH DISPOSAL

- Dust/ Ash collected from:
  - Bottom of Furnace,
  - Bottom of Economizer
  - Bottom of Air Pre-heater, &
  - Electrostatic Precipitator.
- Collected into Hoppers
- Sent into Storage Bin
- Transported as Dry/Wet Fly Ash



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STEAM GENERATING PLANT

- Steam Generating Plant Components
- Basic Steam Cycle
- Boiler Furnace
- Boiler
- Super Heater
- Economizer
- Air Pre-heater

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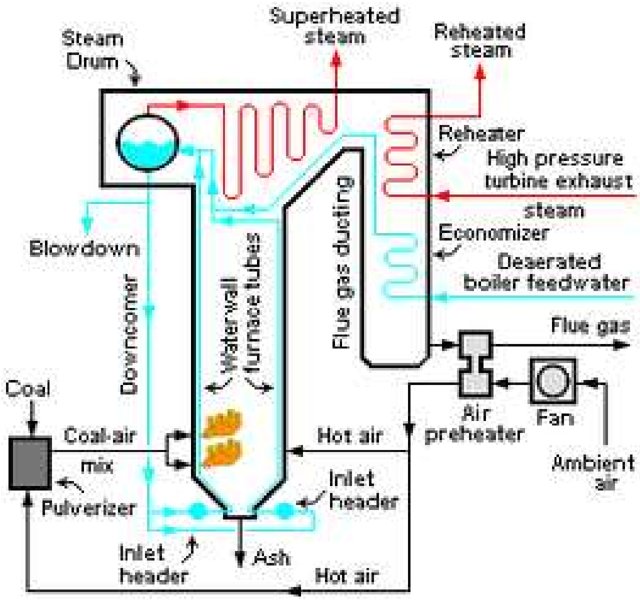
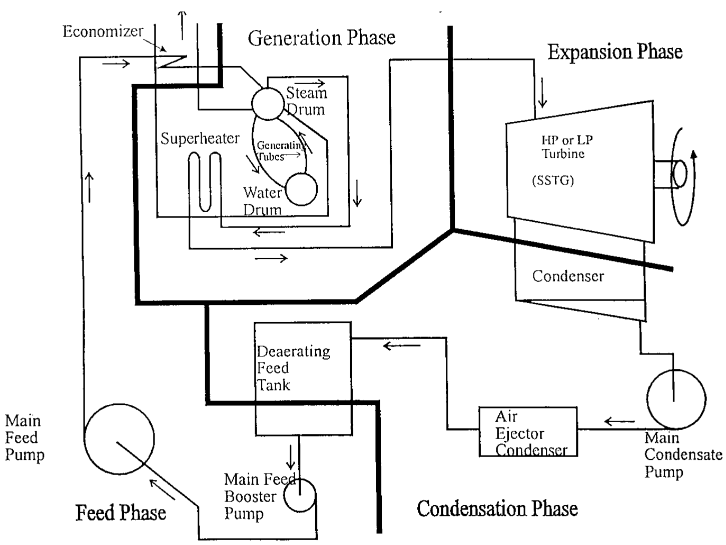
STEAM GENERATING PLANT

- Components :
  - Boiler Furnace
  - Boiler
  - Steam Drum
  - Super Heater
  - Re-heater
  - Economizer
  - Air Pre-heater
  - Forced Draft Fan



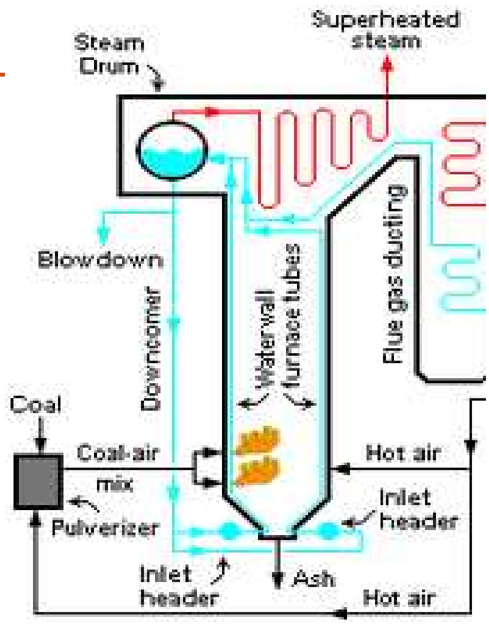
BASIC STEAM CYCLE



Phases of Basic Steam Cycle:
- Feed Phase
- Generation Phase
- Expansion Phase
- Condensation Phase

BOILER FURNACE

- **Boiler Furnace:** is a chamber in which fuel is burnt to liberate the heat energy, in addition, it provides support and enclosure for the combustion equipment.
- Furnace walls are made of refractory materials (fire clay, silica, kaolin etc.).
- Types of construction:
  - Plain Refractory Walls
  - Hallow Refractory Walls with air cooling
  - Water Walls
- Water walls is the recent development.



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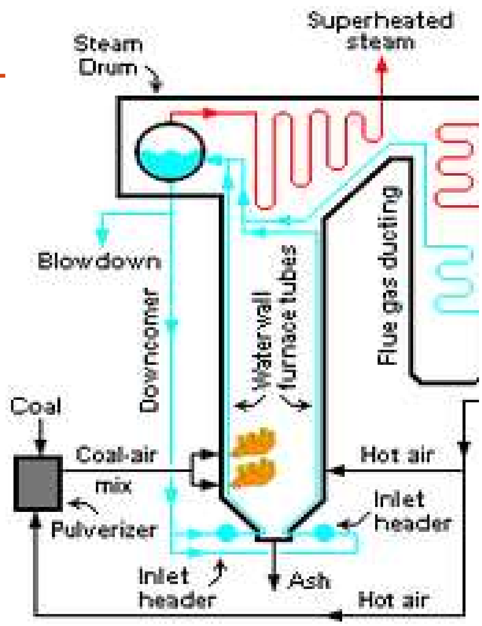
BOILER FURNACE

- Water Walls:
  - Consists of plain tubes arranged in side by side and on the inner face of the refractory walls.
  - The tube are connected to the upper & lower headers of the boiler.
  - The water is made to circulate through these tubes.
  - Water walls absorb the radiant heat in the furnace which would otherwise heat up the furnace walls.



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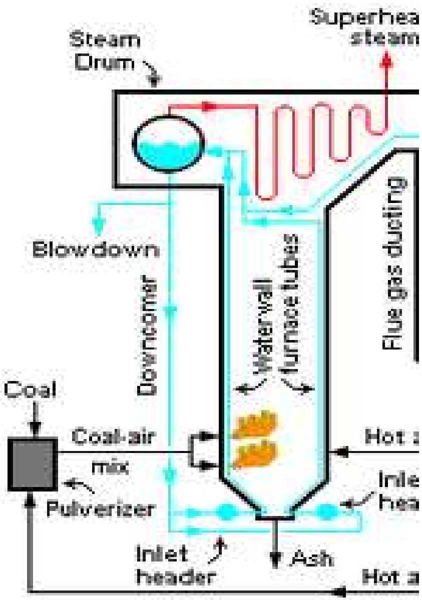
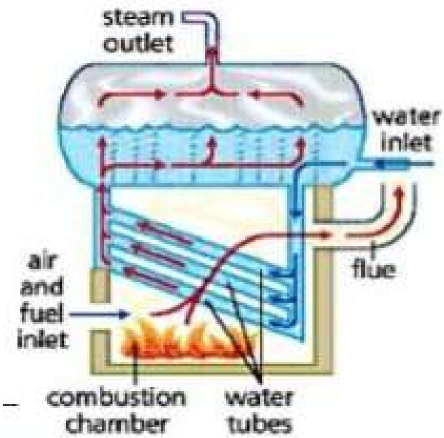
BOILER

- Boiler: is a device wherein water is converted into steam by utilizing the heat of combustion
- Types:
  - Fire Tube: Hot combustion gases pass through tubes which are surrounded by water.
  - Water Tube: Water flows through the tubes and hot combustion gases flow over the tubes.



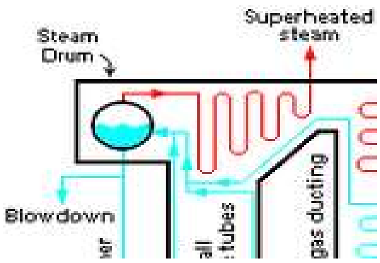
BOILER

- For large power plants – Water tubes are suitable
- Unique features of Water Tube Boiler:
  - Method of water circulation
  - Types of tubes used
  - Improved method of heating
- Advantages of Water tube boiler:
  - Requires less space,
  - Better overall control,
  - Safe operation,
  - Better efficiency



SUPER HEATER

- It rises the temperature of steam above the boiling point of water.
- Increases overall efficiency of the plant.
- Contains group of special alloy steel (chromium molybdenum).
- Steam produced in the boiler is super heated by the heat of the flue gases.
- Types:
  - Radiant Type
  - Convection Type



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TYPES OF SUPER HEATER

- Radiant Type:
  - Normally located in furnace between water walls and absorbs heat from the burning fuel through radiation.
  - Disadvantages:
    - Has drooping characteristics: Temperature decreases with increase in steam output.
    - Gets overheated, so care should taken while designing.
  - Not favored these days
- Convection Type:
  - Uses the heat of the flue gases to heat the saturated steam through a convective heat transfer process.
  - Advantages:
    - Has a rising characteristics: Temperature increases with increase in steam output.
  - Most commonly used

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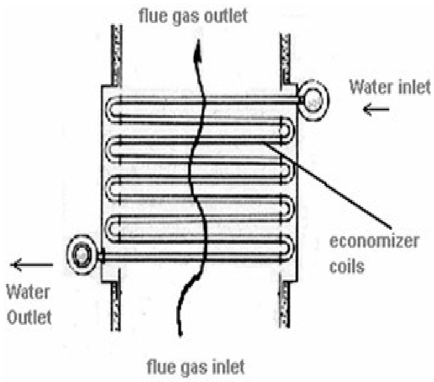
ECONOMIZER

- Heats feed water on its way to the boiler using heat from flue gases thus rising boiler efficiency.
- Reduces stress on the boiler with raised temperature of the feed water to the boiler.
- Contains a large number of thin walled small diameter closely packed parallel tubes connected by headers of drums.
- Advantages:
  - Rising boiler efficiency
  - Saving the fuel
  - Reduced pressure in the boiler due to high temperature of feed water



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AIR PREHEATER

- Super heater and Economizer and can't fully extract the heat from flue gases.
- Air preheaters are used to recover some of the heat escaping with these gases.
- Used to heat air being supplied to the furnace for coal combustion.
- This improves the efficiency of the plant.
- Types:
  - Recuperative
  - regenerative

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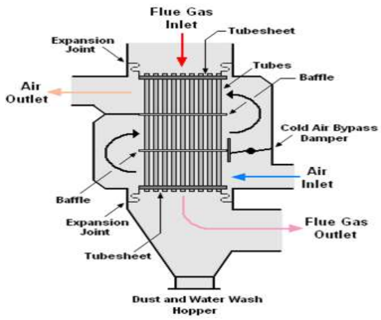
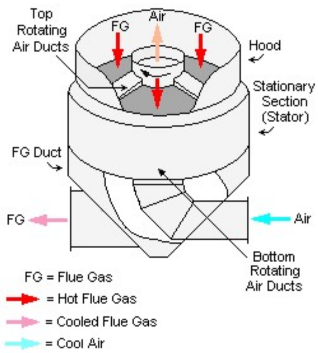
AIR PREHEATER TYPES

- Recuperative:
  - Contains a group of steel tubes.
  - Flue gases pass through tubes while the air flows externally to the tubes.
- Regenerative:
  - Contains slowly moving drum of corrugated metal plates.
  - Flue gases flow continuously on one side of the drum and air on the other side.
  - This action permits the transfer of heat of flue gases to the air being supplied to the furnace for coal combustion.





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STEAM TURBINE

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- Steam Prime Mover
- Steam Engine vs. Steam Turbine
- Types of Steam Turbine
- Impulse Turbine
- Reaction Turbine

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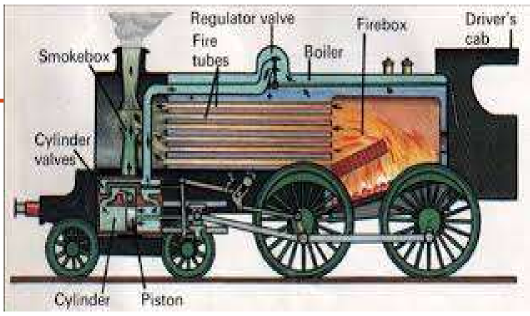
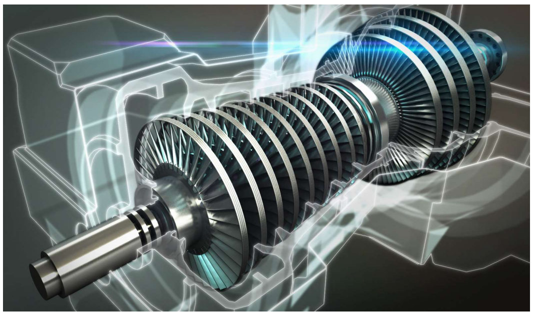
STEAM PRIME MOVER

- Converts steam energy in mechanical energy.
- Steam Prime Mover Types:
  1. Steam Engine or Reciprocating Engine
  2. Steam Turbine

1. **Steam Engine** will have Piston, whereas,
2. **Steam Turbine** will have Vanes

- **Steam Turbine** has several **advantages over** steam engine.





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STEAM ENGINE VS. STEAM TURBINE

- Steam turbine has several advantages over steam engine.
  - No Flywheel is required
  - No piston is needed
  - No slice valve is required
  - Can be built in large as much as 1000MW
  - Higher thermodynamic efficiency since the steam can be expanded to lower final temperature unlike in steam engine

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STEAM TURBINE

- In Steam Turbine the heat energy of the steam at higher temperature is converted into KE by passing the stem through nozzles.
- Fluid Energy = KE + Pressure+ Temperature
- Pressure + Temp = Enthalpy
- High Enthalpy gives higher energy conversion
- Types of Steam Turbine
  - Impulse Turbine
  - Reaction Turbine
  - Series Combination of both (is a commercial approach to use steam more efficiently by keeping both blading on the same shaft.

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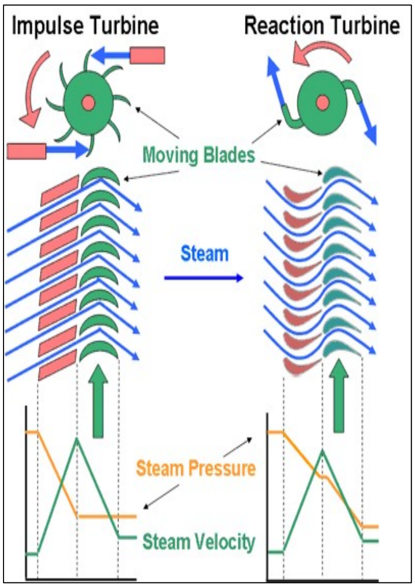
IMPULSE VS. REACTION TURBINES

- The steam is coming out, at very high velocity through fixed nozzles, impinges on blades fixed on the periphery of the rotor.
- The expansion of steam takes place in the nozzles and not in the turbine blades.
- The blades changes the direction of the steam flow without changing its pressure.
- Change in momentum gives rotation to the shaft.



- Steam is partially expanded in the stationary nozzles and the remaining expansion takes place during its flow over the moving blades.
- The change in momentum of steam causes a reaction force on the moving blades, which sets the rotor in motion.
- The shaft rotates in a direction opposite to the direction of steam jet.

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59 ALTERNATOR/ GENERATOR

- About Alternator
- Cooling of Alternator

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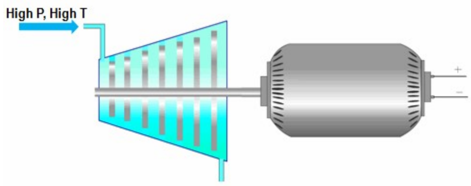
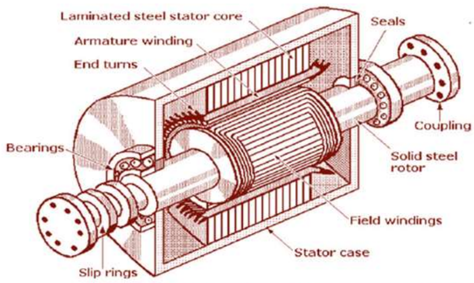
ALTERNATOR

- Rotor of Alternator is coupled to turbine rotating shaft.
- Thus, converts mechanical energy developed in turbine into electrical energy.
- Alternator coupled to steam turbine are called turbo-alternators.
- All high capacity alternators are 2 pole machines. And speed is of range 3000rpm for 50Hz supply.

$$N_S = \frac{120 \, X \, f}{P}$$

Where N_S is synchronous speed in rpm, f is frequency and P is number of poles of the machine.





Cutaway view of a synchronous AC generator with a solid cylindrical rotor capable of high-speed rotation.

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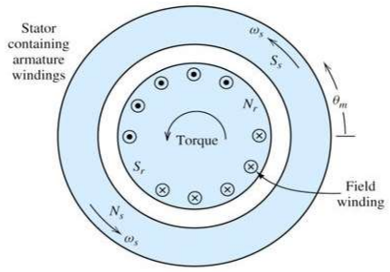
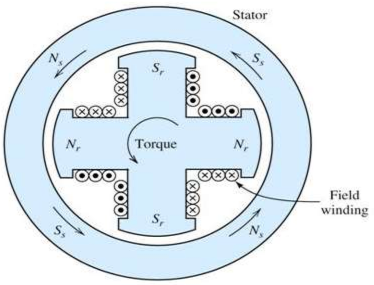
ALTERNATOR

- The rotor may be:
  - Cylindrical Type
    - Smaller in Diameter
    - Longer in Length
    - Longer Air Gap
    - High Speed Operation
    - Steam Power Plant
  - Salient Pole Type
    - Low Speed Operation
    - Larger diameter and small length
    - Hydro Power Plant
    - Diesel Power Plant
    - For same size rating is lower than cylindrical rotor type





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COOLING OF ALTERNATOR

- Upto 100 MW – Air Cooling
- Large Machines – Hydrogen Cooling (above 500 MW – Forced Hydrogen)
- Advantages of Hydrogen Cooling:
  - Windage losses are reduced by 10%
  - For same frame size, it is possible to get 25% more power because of higher thermal conductivity of hydrogen
  - Increases the life of insulation
  - No fire hazard as hydrogen does not support combustion
  - With increase in hydrogen power, output of generator increases
- However,
  - Mixture of hydrogen and air may cause explosion
  - The generator enclosure must be air tight
  - Special oil gland seal on the bearings should be provided to keep hydrogen leakage at a safe minimum.

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FEED WATER CIRCUIT

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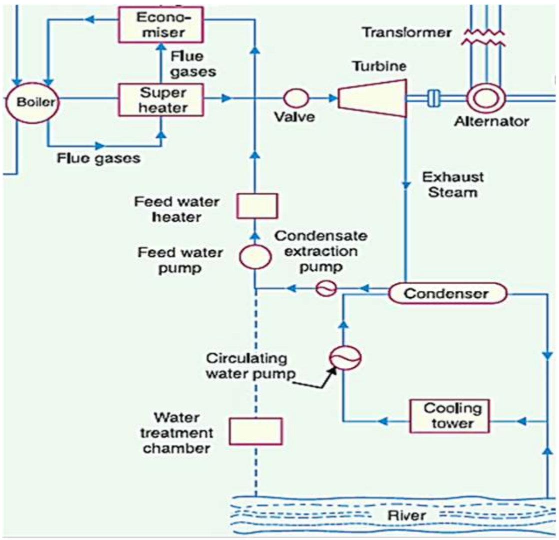
FEED WATER CIRCUIT

- Initially water pumped from reservoir to a separate water softening plant to remove all impurities.
- Impurities in water causes corrosion and erosion of boiler tubes, turbine blades, condenser tubes. This creates blockages in the boiler tubes resulting overheating of tubes.
- The steam output is condensed in the condenser and again fed into the boiler. Some steam is lost through out the process of steam generation to condensation.
- A 400 MW pant requires 100 to 500 tons of water per hour as make-up water.



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COOLING WATER CIRCUIT

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- Condenser
- Cooling Tower

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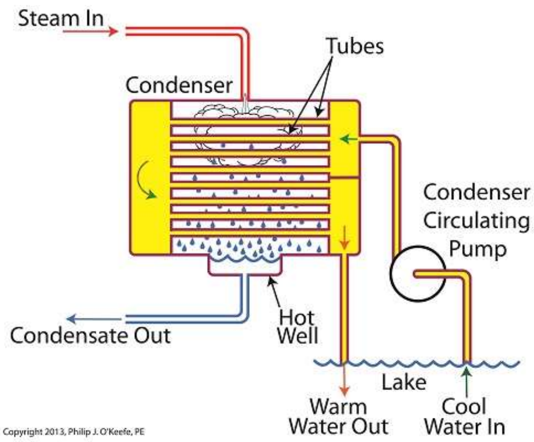
CONDENSER

- Condenser is a device in which the exhaust steam from steam turbine is condensed by means of cooling water.
- The main purpose of a steam condenser in turbine is to maintain a low back pressure on the exhaust side of the steam turbine.
- After releasing from nozzles, the steam has to expand to a great extent for converting available energy into it to usable mechanical work.
- So, if the steam after doing its, work, does not get condensed, it will not give required space to other steam behind it, to expand to its required volume.



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CONDENSER TYPES

- Jet Type:
  - Here cooling water is sprayed on the exhaust steam.
  - This is very fast process of condensing steam. But here cooling water and condensed steam are mixed up which can not be separated.
- Surface Type:
  - Here, cooling water and exhaust steam are separated by a barrier and condensation is done by heat exchanging through this barrier wall.
  - Cooling water is passed through numbers of water tubes and exhaust steam passes over the outer surface of the tube.
  - The heat of steam is absorbed by the water inside the tube through the wall of the tube.
- Surface steam condensing is slower process than Jet Steam condensing, but the main advantage of surface steam condensing is that, the condensed steam is not thrown to waste but is returned to boiler through feed water system.
- Surface condenser are commonly used type.

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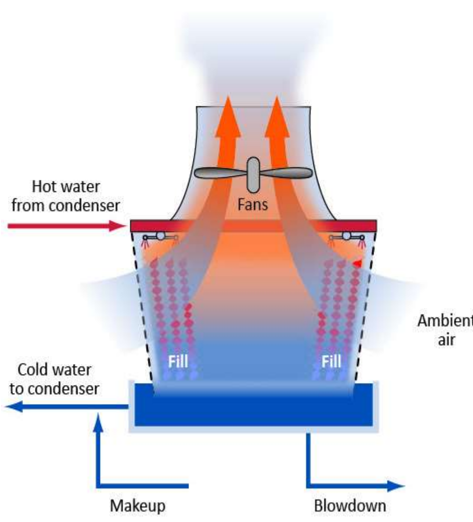
COOLING TOWER

- Hot water from the condenser is further cooled down using cooling tower.
- In this the large amount of water is divided to fall as droplets.
- These droplets will fall from the height of 8 to 10m to the bottom of the tower.
- This splitting of water, the draught and large evaporation surface helps to cool water very quickly.
- The water from the base is pumped back to the condenser, this cycle is repeated.
- Some water is lost owing to evaporation.
- Induce draft fan is used as power requirement of forced draft fan is more.



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CHIMNEY

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CHIMNEY

- A **Chimney** or **flue-gas stack** is a vertical pipe, channel through which flue gases are exhausted to the outside air.
- Flue gas is usually composed of CO_2 and water vapour contains a small percentage of pollutants.
- These are often quite tall, up to 400 metres (1300 feet) or more, so as to disperse the exhaust pollutants over a greater area and thereby reduce the concentration of the pollutants to the levels required by environmental policy and regulations.

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EFFICIENCY OF TPS

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EFFICIENCY

- Thermal Efficiency $(\eta_{Thermal}) = \frac{\textit{heat equivalent of mechanical energy given to turbine shaft}}{\textit{heat of coal combustion}}$

- Overall Efficiency $(\eta_{Overall}) = \frac{\textit{heat equivalent of electrical output}}{\textit{heat of coal combustion}}$

- Overall Efficiency = (Thermal Efficiency) X (Electrical Efficiency) **or**
  = (Thermal Efficiency of Turbine including Condenser) X (Boiler Efficiency) X (Electrical Efficiency)

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EFFICIENCY

- Approximate Heat Balance Sheet:
  - Work done/ Thermal Efficiency - 28%
  - Friction & Windage Losses - 01%
  - Heat to circulating water - 65%
  - Heat in condensate to be returned - 06%

- It is seen that major part of heat goes to circulating water
- Typical values of Generator Efficiency - 97% for small machines
  - 98-99% for large machines
- Thermal efficiency of turbine - 28% (24-32%)
- Boiler efficiency with economizer and pre heater - 87-90%
- ***Overall Thermal Plant Efficiency - 18-24%***

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(DIS)ADVANTAGES

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ADVANTAGES AND DISADVANTAGES

- Advantages:
  - The fuel cost is less
  - Less initial cost compared to hydro, nuclear power plants
  - Can be installed at any location
  - Requires less space compared to hydro
  - Cost of generation is less than diesel generation plant
- Disadvantages:
  - Pollutes atmosphere
  - Running cost is more when compared to hydro power plant.

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77 # HYDROPOWER PLANT

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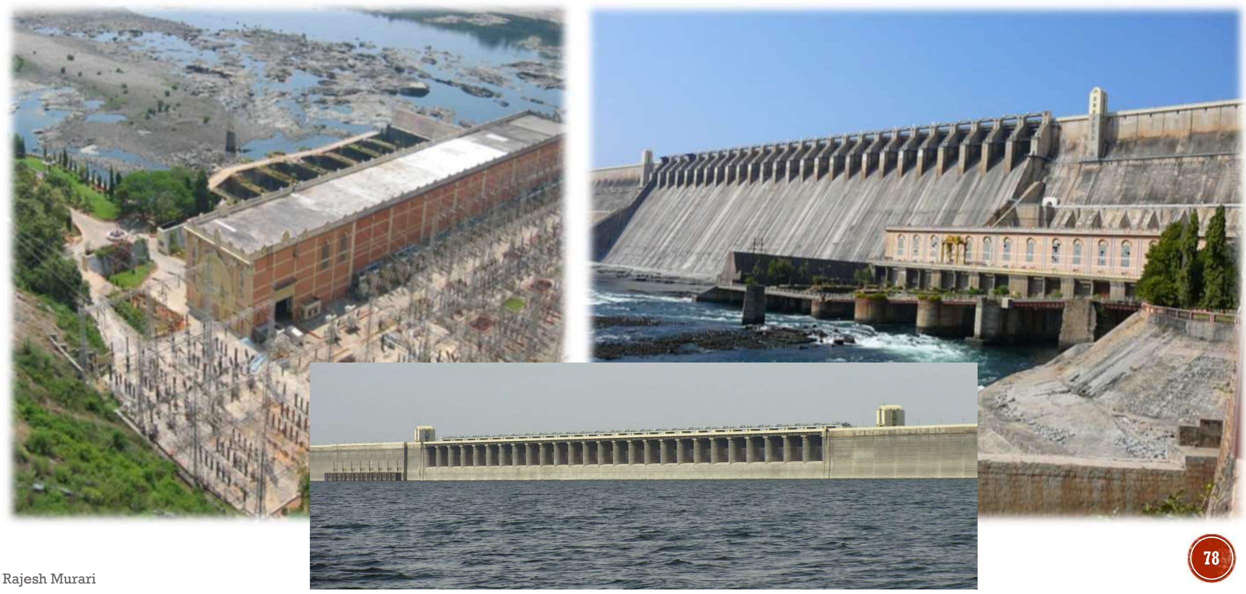
HYDROPOWER PLANT (NAGARJUNA SAGAR)



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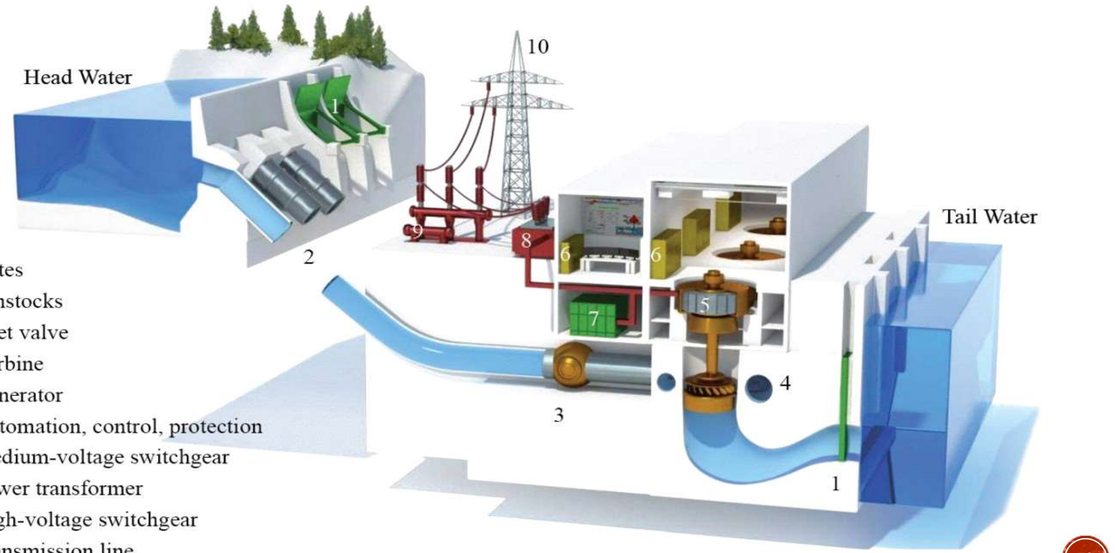
HYDROPOWER PLANT



1 Gates
2 Penstocks
3 Inlet valve
4 Turbine
5 Generator
6 Automation, control, protection
7 Medium-voltage switchgear
8 Power transformer
9 High-voltage switchgear
10 Transmission line

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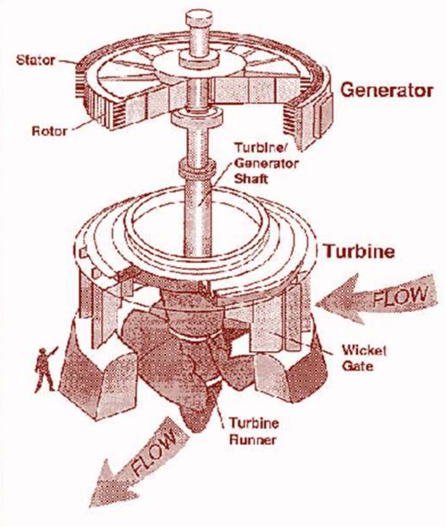
HYDROPOWER PLANT



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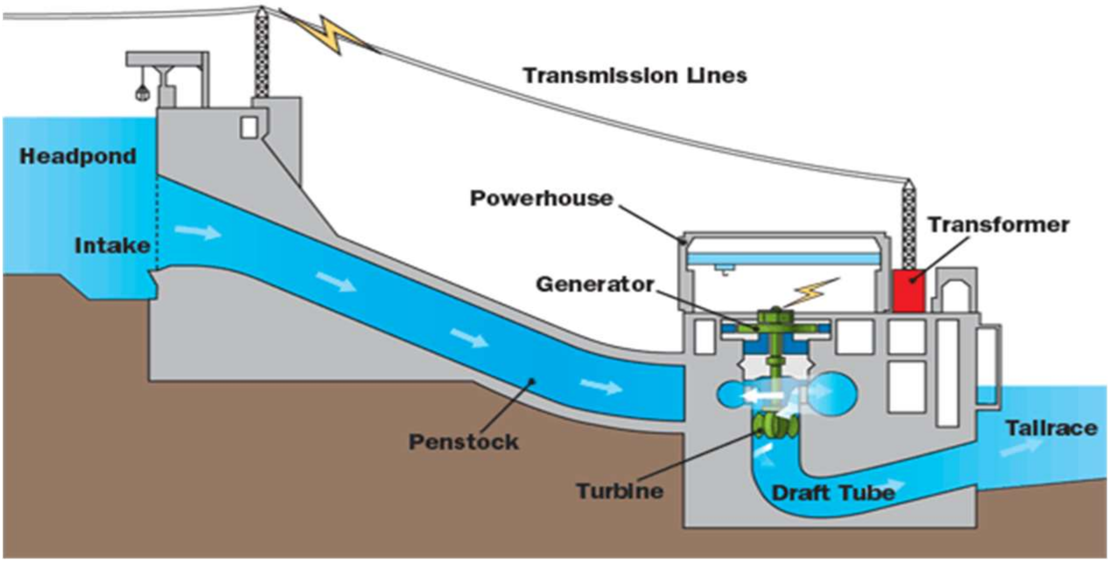
HYDROPOWER PLANT



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ADITYA COLLEGE OF ENGINEERING AND TECHNOLOGY

NUCLEAR POWER STATIONS

1

Unit-II

Power Systems -I

B. Tech (II Year, II Semester)

Electrical & Electronics Engineering

CONTENTS

INTRODUCTION

- A **nuclear power plant** is a thermal power station in which the heat source is a nuclear reactor.
- As is typical in all conventional thermal power stations the heat is used to generate steam which drives a steam turbine connected to a generator which produces electricity.
- As of 23rd April 2014, the IAEA report there are 449 nuclear power reactors in operation in 31 countries.

APPLICATIONS OF NUCLEAR ENERGY

***USS Enterprise*, the longest ever naval vessel, and the first nuclear-powered aircraft carrier.**

APPLICATIONS OF NUCLEAR ENERGY

The VMF Typhoon class submarine, is nuclear-powered and the world's largest-displacement submarine.

APPLICATIONS OF NUCLEAR ENERGY

The only US aircraft to carry a nuclear reactor was the NB-36H. The program was cancelled in 1958

APPLICATIONS OF NUCLEAR ENERGY

SNAP-10A was an experimental nucle ar reactor launched into space in the 1960s.

Russia has sent about 40 reactors into space and its TOPAZ-II reactor can produce 10 kilowatts.

APPLICATIONS OF NUCLEAR ENERGY

Kudankulam Nuclear Power Plant is a nuclear power station in Kudankulam, Tamil Nadu. The plant's first reactor is the first Pressurised Water Reactor (PWR) belonging to the Light Water Reactor (LWR) category in India, and the 21st nuclear power reactor in the country.

NUCLEAR ENERGY STATISTICS (WORLD)

- Electricity was generated by a nuclear reactor for the first time ever on September 3, 1948 at the X-10 Graphite Reactor in Oak Ridge, Tennessee in the United States, and was the first nuclear power plant to power a light bulb.
- The second, larger experiment occurred on December 20, 1951 at the EBR-I experimental station near Arco, Idaho in the United States.
- On June 27, 1954, the world's first nuclear power plant to generate electricity for a power grid started operations at the Soviet city of Obninsk.
- The world's first full scale power station, Calder Hall in England opened on October 17, 1956.

NUCLEAR ENERGY STATISTICS (WORLD)

Source of Electricity (World total year 2014)

-	Coal	Oil	Natural Gas	Nuclear	Renewables	other	Total
Average electric power (TWh/year)	8390	879	4744	**2344**	3819	898	21,161
Average electric power (GW)	942.6	126.7	490.7	**311.6**	375.1	64.8	2311.4
Proportion	40%	4%	23%	**11%**	19%	2%	100%

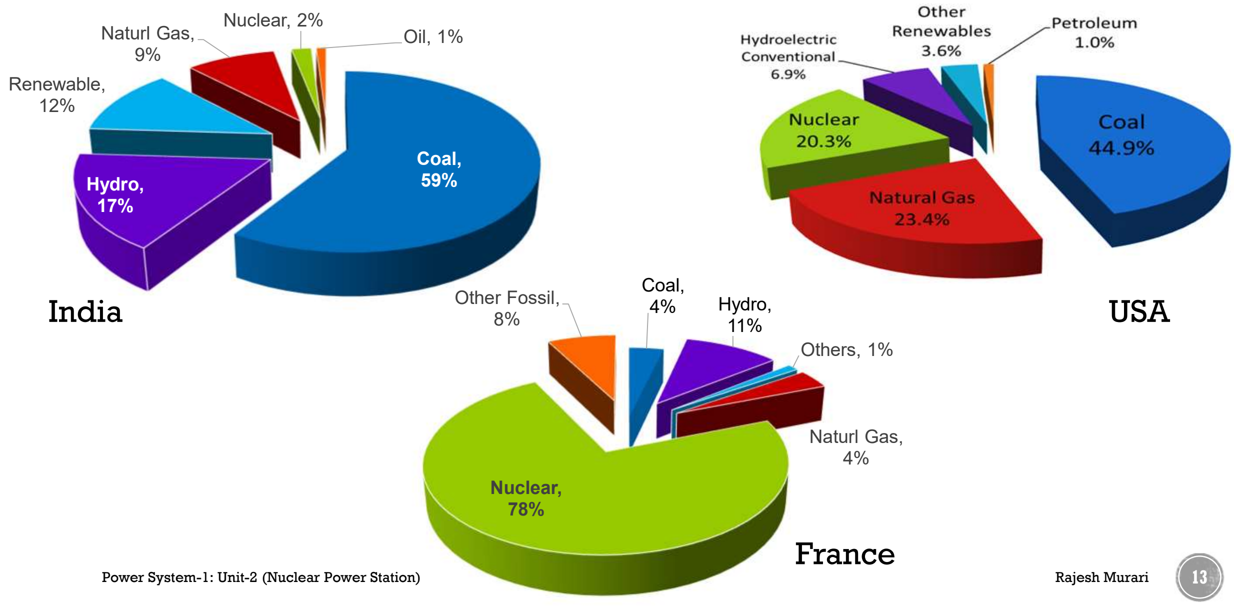
NUCLEAR ENERGY STATISTICS (INDIA)

- As of 2016, India has 22 nuclear reactors in operation in eight nuclear power plants,
- Having an installed capacity of 6,780 MW and producing a total of 35,000 GWh of electricity
- Six more reactors are under construction and are expected to generate an additional 4,300 MW.
- India drew up "an ambitious plan to reach a nuclear power capacity of 63,000 MW in 2032"

NUCLEAR ENERGY STATISTICS (INDIA)

- India's first research nuclear reactor and its first nuclear power plant were built with assistance from Canada.
- The 40 MW research reactor agreement was signed in 1956, and CIRUS achieved first criticality in 1960. (on the assurance that it would not be used for military purposes)
- The agreement for India's first nuclear power plant at Rajasthan, RAPP-1, was signed in 1963, followed by RAPP-2 in 1966. (not for a military programme).
- The 200MWe RAPP-1 reactor was based on the CANDU reactor began operation in 1972.
- The USA and Canada terminated their assistance after the detonation of India's first nuclear explosion in 1974.

NUCLEAR ENERGY STATISTICS



NUCLEAR ENERGY STATISTICS (INDIA)

Power station	State	Units	Total capacity (MW)
Kaiga	KA	220 x 4	880
Kakrapar	GJ	220 x 2	440
Kalpakkam	TN	220 x 2	440
Narora	UP	220 x 2	440
Kota	RJ	100 x 1 200 x 1 220 x 4	1180
Tarapur	MH	160 x 2 540 x 2	1400
Kudankulam	TN	1000 x 1	1000
		21	**5780**

NUCLEAR ENERGY STATISTICS (INDIA)

The planned projects are:

Power station	State	Units	Total capacity (MW)
Gorakhpur	Haryana	700 x 4	2,800
Chutka	Madhya Pradesh	700 x 2	1,400
Mahi Banswara	Rajasthan	700 x 2	1,400
Kaiga	Karnataka	700 x 2	1,400
Kalpakkam	Tamil Nadu	500 x 2	1,000
Site to be decided		300 x 1	300
Kudankulam	Tamil Nadu	1000 x 2	2000
Jaitapur	Maharashtra	1650 x 6	9900
Kovvada	Andhra Pradesh	1594 x 6	9564
Mithi Virdi (Viradi)	Gujarat	1100 x 6	6600
	Total	**33**	**36364**

BASICS (EINSTEIN'S ENERGY LAW)

- Mass can be converted into energy with yield governed by the Einstein Relationship:

$$E = mc^2$$

Where c is the speed of the light.

The energy from converting one kilogram is:

$$E = (1\ kg)(3X10^8)^2 = 9X10^{16}\ joules$$

The energy consumption for one citizen for one year is about $5X10^{11} joules$

BASICS

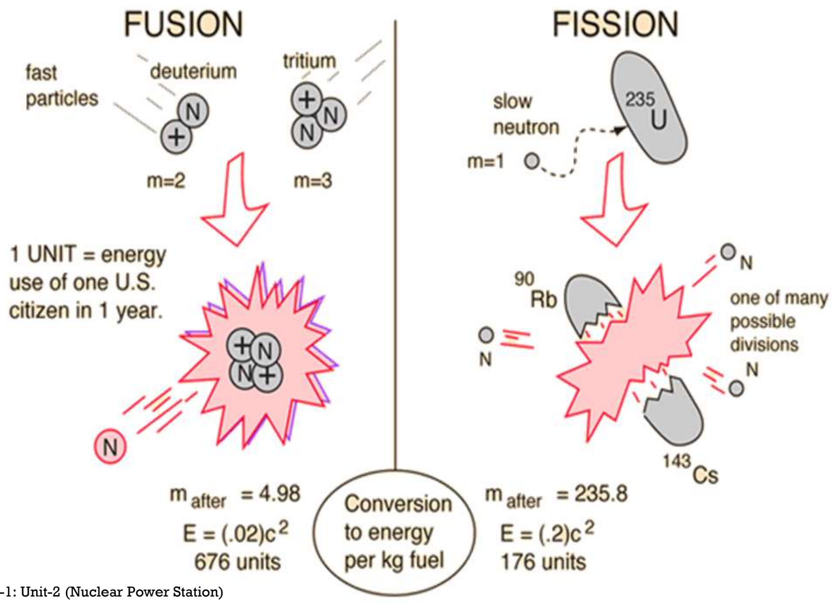
(fuel for $5X10^{11}$ J=$0.012X10^{11}$ kcal=2,777 MW)

- Mass Conversion : 0.0056 grams
- Coal : 20 tons
- Natural Gas : 5,00,000 cubic feet
- Oil : 10,600 liters

BASICS

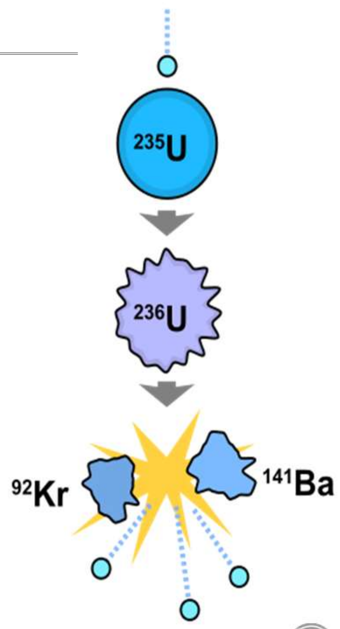
- However, direct mass conversion is not possible on a large scale. A fraction of the mass can be converted to energy by:
- Nuclear Fission: the breaking up of heavy nuclei
- or
- Nuclear Fusion: the combining of light nuclei

BASICS



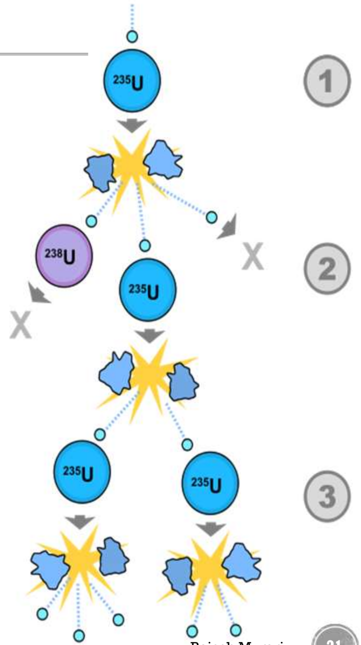
NUCLEAR FISSION

- The term fission means the explosion or disintegration of a nucleus into two or more component parts, as a result of a particle entering or combining with the nuclei.
- When a neutron collides with the ^{235}U nucleus, it is absorbed by the ^{235}U nucleus and forms a compound nucleus ^{236}U.
- ^{236}U being unstable fissions into two major pieces, called fission fragments, plus neutrons and release energy.



CHAIN REACTION

- A ^{235}U atom absorbs a neutron and fissions into two new atoms (fission fragments), releasing three new neutrons and some binding energy.
- One of those neutrons is absorbed by an atom of ^{238}U and does not continue the reaction. Another neutron is simply lost and does not collide with anything, also not continuing the reaction. However, one neutron does collide with an atom of ^{235}U, which then fissions and releases two neutrons and some binding energy.
- Both of those neutrons collide with ^{235}U atoms, each of which fissions and releases between one and three neutrons, which can then continue the reaction.



NUCLEAR FUEL

- Uranium is the fuel used in nuclear power plants
- It is non-renewable and has two isotopes, ^{235}U about 0.7% and ^{238}U, 99.3%.
- Materials fissionable by thermal or low speed neutrons are ^{233}U, ^{235}U and ^{239}Pu
- ^{233}U, and ^{239}Pu are not found in nature but ^{238}U and ^{232}Th can produce them by nuclear reactions. These materials are known as fertile materials (^{238}U and ^{232}Th)
- ^{238}U is bombarded with slow neutrons it produces $^{239}U_{92}$ (half life 23.5 min) which is unstable and undergoes two beta disintegrations. The resultant ^{239}Pu has a half life 2.44×10^4 years and is good alpha emitter.

NUCLEAR FUEL

- In Britain, the fuel for most of the reactors is natural uranium since it is abundantly available.
- USA – enriched uranium
- India
  - Reactor in Kota – natural uranium
  - Tarapur – enriched uranium
- The plants which use natural uranium are larger in size compared to the plants that use enriched uranium.

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NUCLEAR POWER STATIONS

Unit-II

Power Systems -I

B. Tech (II Year, II Semester)

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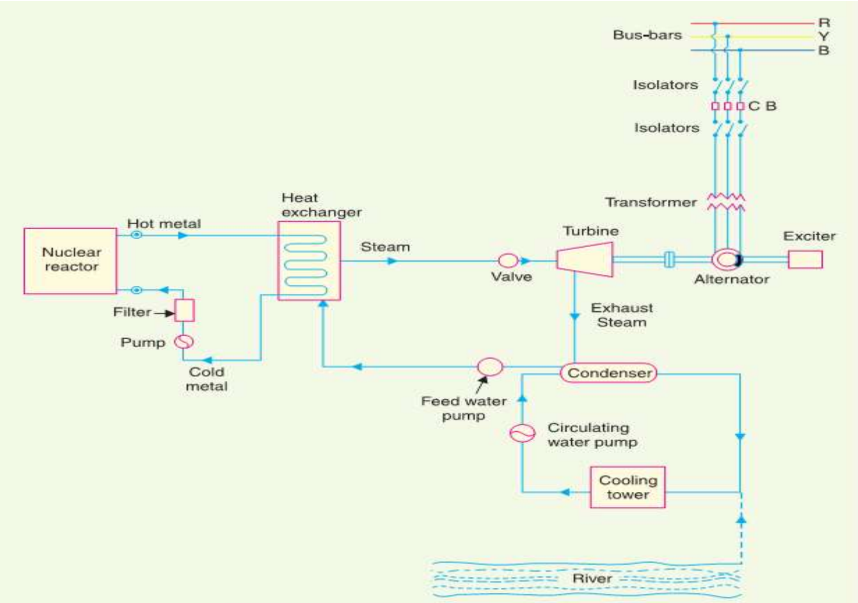
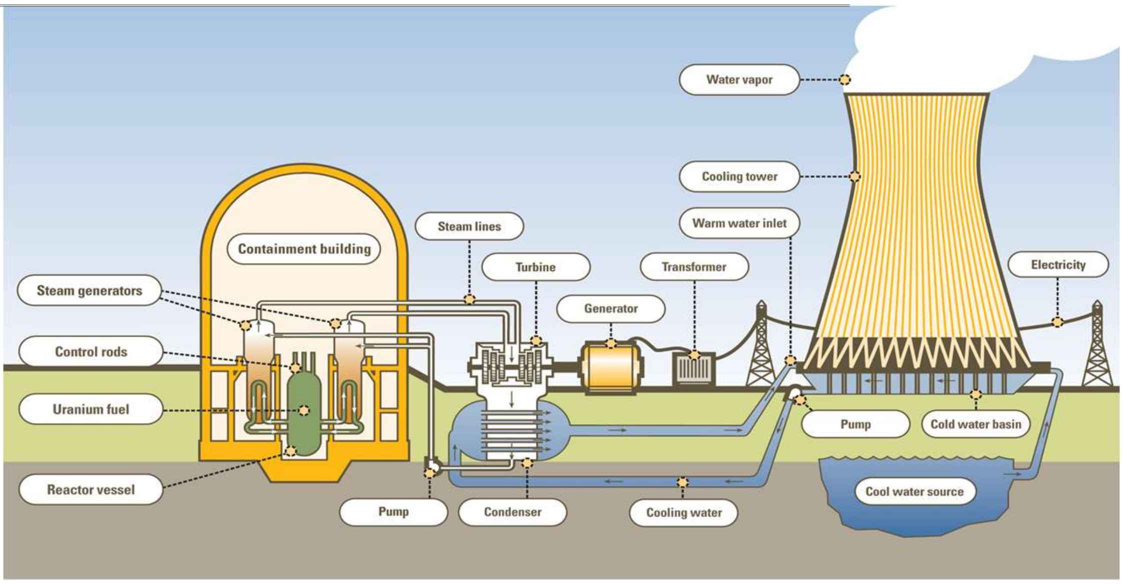
SCHEMATIC DIAGRAM OF NUCLEAR POWER STATION

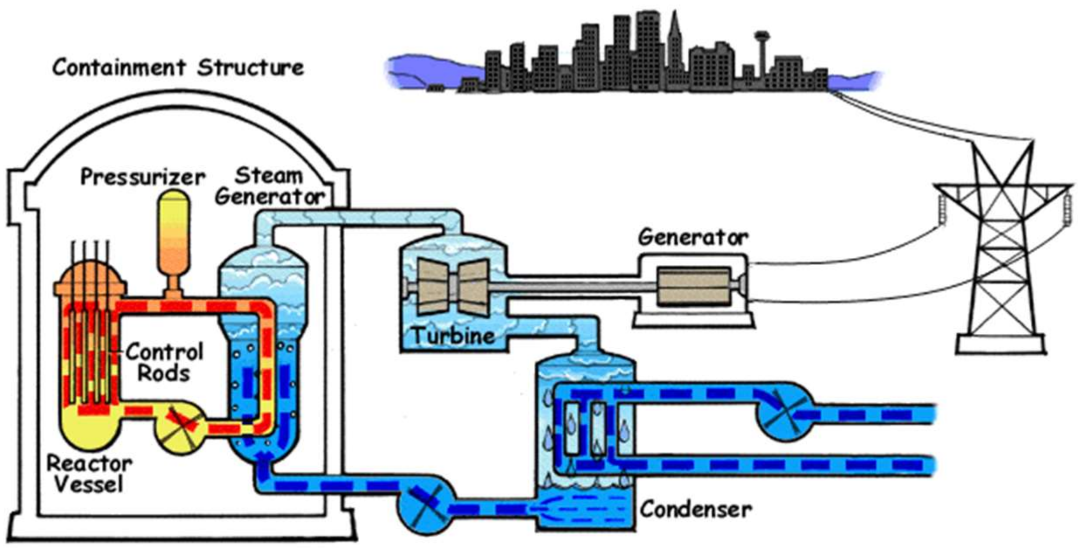


Schematic arrangement of Nuclear Power Station

WORKING PRINCIPLE



WORKING PRINCIPLE

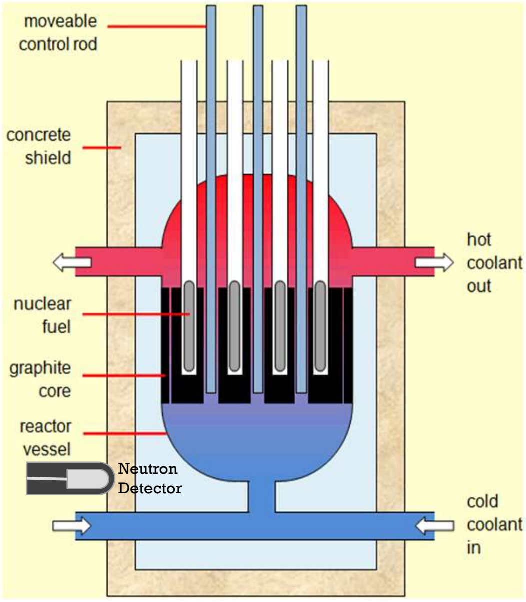


NUCLEAR REACTOR COMPONENTS

- A nuclear reactor is a device in which energy is made available through controlled nuclear reaction.
- The main parts of the nuclear reactor:
  1. Reactor Core: in which the nuclear reaction takes place and energy is released
  2. Control System: used for controlling the rate of energy released
  3. Cooling System: A method of extracting the energy such as a cooling system which could remove heat from the core
  4. Shielding: A biological shield to protect the personal against radiation emitted from the reactor.

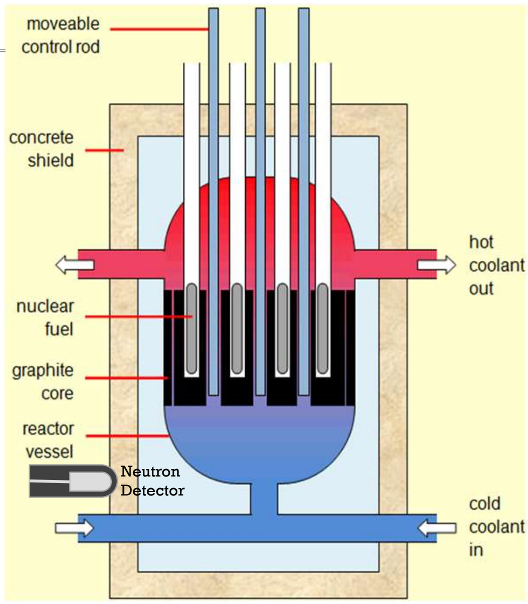
REACTOR CORE

- Contains a number of fuel rods made of fissile material.
- For cladding (the process of protecting one metal by bonding a second metal to its surface) of the nuclear fuel should be resistant to absorption, have a low neutron cross section, bond well to fuel and low cost. (Aluminum, Stainless steel, and Zirconium)
- It is desirable to use reactor core as cubical or cylindrical in shape as it facilitates the refueling operation and simplifies the process of circulation of coolant through the core.



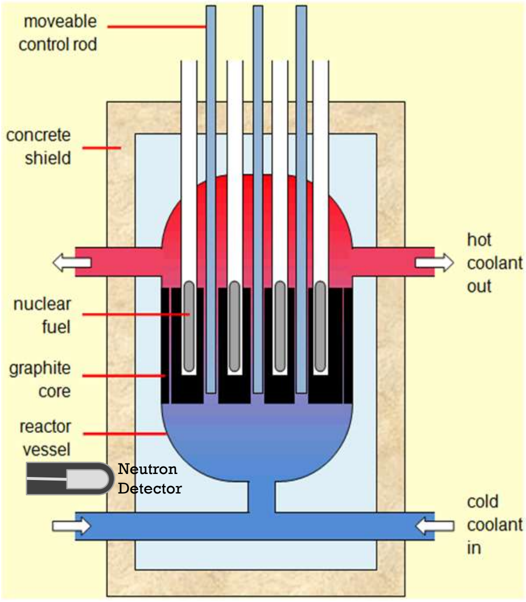
REACTOR CORE

- Moderator: is used to slow down the neutrons by absorbing some of the KE of the neutrons by direct collision, thereby increasing the chances of fission.
- Requirement of moderator is the weight of nucleus should be less.
- Materials used: Graphite, Ordinary (Light) Water, Heavy Water.
- Graphite is simple to fabricate and handle, and does not pose any contamination.
- Light water should be without any impurities.
- Heavy water is costlier per unit weight. The resultant size of the reactor is more compact.



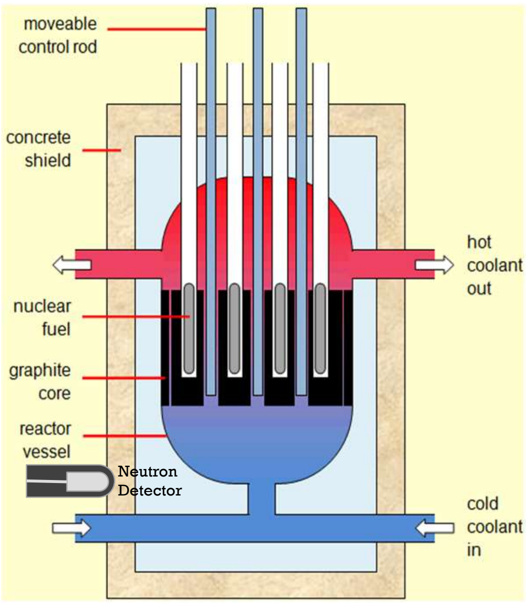
REACTOR CORE

- **Reflector:** A neutron reflector is placed around the core and used to avoid the leakage of neutron from the core
- It reflects back the neutron and used for the conversion of non-fissionable material to fissionable material,
- And thereby increasing the efficiency of the reactor.
- Also helps in bringing a more uniform distribution of heat produced in the reactor core.
- **Materials used:** Reactor grade Graphite



CONTROL SYSTEM

- Involves insertion of a material having high absorption cross section for thermal neutrons, into the core.
- **Materials used:** Cadmium and Boron
- Types of Control Rods:
  - Safety Rods
  - Shim Rods and
  - Regulating Rods
- And thereby increasing the efficiency of the reactor.
- Also helps in bringing a more uniform distribution of heat produced in the reactor core.



CONTROL SYSTEM

- **Safety Rods:** As long as, are inserted into the core, it stops generation and when they are removed completely from the core, it starts generating.
- **Shim Rods:** are withdrawn from the core through small displacement at intervals, so as to compensate for fission products built-up I the fuel.
  - Fission products are analogous to ash in coal fired plants and they slow down the output of the reactor.
  - These rods are usually partially withdrawn during start-up and are left in one position for a long period at a constant level operation.
- **Regulating Rod**: The load on the system keeps on changing from time to time. These changes are taken care by regulating rod. These rods should be adjusted continuously.

COOLING SYSTEM

- For large nuclear power plants closed loop coolant system is used, which means the coolant passing through the reactor is recirculated and not passed through turbine and discharged.
- This avoids the discharge of radio active material into the atmosphere or rivers.
- By designing suitable heat exchanger, it is possible to obtain suitable combination of temperature and pressure for higher efficiency, in a secondary fuel than in primary fluid.
- **Coolants:** Boiling Water (in USA), Liquid metals like sodium-potassium alloy, Carbon di-oxide (in Britain).

TYPES OF NUCLEAR REACTORS

- **Based on the neutron energy:**
  - **Thermal Reactors:** are those in which the neutrons are slowed down with a material called moderator to a velocity of about 2000m/s before they collide with the nucleus of the fission fuel.
    - This is done to increase the probability of fission as compared to when the neutron moves fast.
    - Most of the reactors in operation as on today are of thermal type.
    - The essential feature is that they would always have a moderator to slow down the neutrons.
  - **Fast Reactors:** are those in which moderator is not used and the neutrons as they are released from fission are used directly for producing fission of additional fuel, without slowing them intentionally.

TYPES OF NUCLEAR REACTORS

- **Classification by moderator material**
  - **Used by thermal reactors**:
    - **Graphite- moderate reactors**
    - **Water moderated reactors**
      - Heavy Water Reactors (used in Canada)
      - Light Water Reactors (most common type of thermal reactors)
  - **Light-element-moderated reactors**: These reactors are moderated by lithium or beryllium.
  - Molten Salt Reactors
  - Liquid metal cooled reactors
  - **Organically Moderated Reactors** (OMR) use biphenyl and terphenyl as moderator and coolant.

TYPES OF NUCLEAR REACTORS

- **Classification by Coolant material used:**
- Water cooled reactor.
  - There are 104 operating reactors in the United States. Of these, 69 are pressurized water reactors (PWR), and 35 are boiling water reactors (BWR)
  - PWR constitute the large majority of all Western nuclear power plants.
    - A primary characteristic of PWRs is a pressurizer, a specialized pressure vessel.
    - Most commercial PWRs and naval reactors use pressurizers.

TYPES OF NUCLEAR REACTORS

- During normal operation, a pressurizer is partially filled with water, and a steam bubble is maintained above it by heating the water with submerged heaters.
- During normal operation, the pressurizer is connected to the primary reactor pressure vessel (RPV) and the pressurizer "bubble" provides an expansion space for changes in water volume in the reactor.
- This arrangement also provides a means of pressure control for the reactor by increasing or decreasing the steam pressure in the pressurizer using the pressurizer heaters.
- PWR are a subset of pressurized water reactors, sharing the use of a pressurized, isolated heat transport loop, but using heavy water as coolant and moderator for the greater neutron economies it offers.

TYPES OF NUCLEAR REACTORS

- **Classification by Coolant material used:**
- Water cooled reactor.
  - **Boiling Water Reactor (BWR)**
    - BWRs are characterized by boiling water around the fuel rods in the lower portion of a primary reactor pressure vessel.
    - A boiling water reactor uses ^{235}U, enriched as uranium dioxide, as its fuel.
    - The fuel is assembled into rods housed in a steel vessel that is submerged in water. The nuclear fission causes the water to boil, generating steam.
    - This steam flows through pipes into turbines. The turbines are driven by the steam, and this process generates electricity. During normal operation, pressure is controlled by the amount of steam flowing from the reactor pressure vessel to the turbine.

TYPES OF NUCLEAR REACTORS

- **Classification by Coolant material used:**
- **Liquid metal cooled reactor:**
  - Since water is a moderator, it cannot be used as a coolant in a fast reactor. Liquid metal coolants have included sodium, NaK, lead, lead-bismuth eutectic, and in early reactors, mercury.
    - Sodium-cooled fast reactor
    - Lead-cooled fast reactor

TYPES OF NUCLEAR REACTORS

- **Classification by Coolant material used:**
- **Gas cooled reactors:** are cooled by a circulating inert gas, often helium in high-temperature designs, while carbon dioxide has been used in past British and French nuclear power plants. Nitrogen has also been used.
  - Utilization of the heat varies, depending on the reactor.
  - Some reactors run hot enough that the gas can directly power a gas turbine. Older designs usually run the gas through a heat exchanger to make steam for a steam turbine.

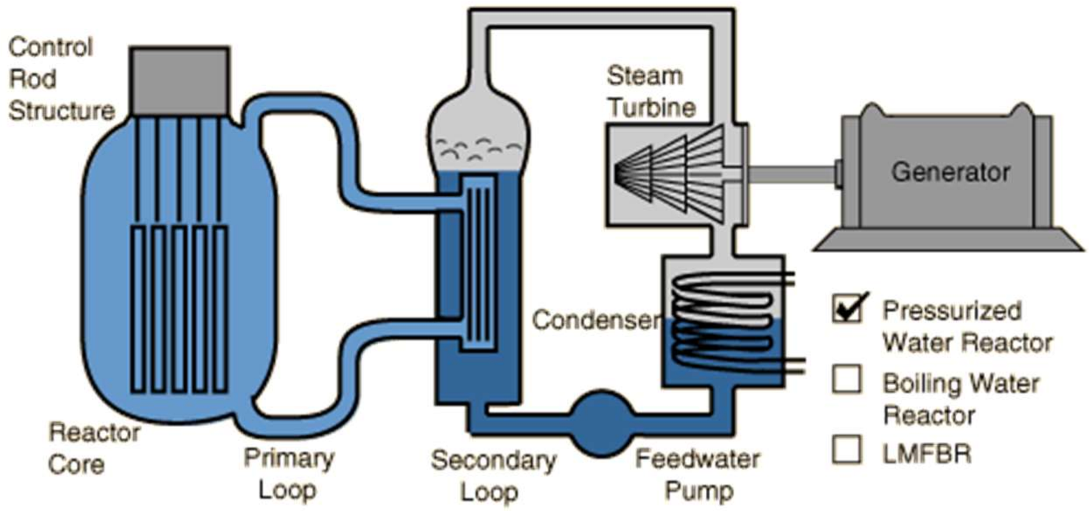
TYPES OF NUCLEAR REACTORS

- **Classification by Coolant material used:**
- **Molten salt reactors (MSRs):** are cooled by circulating a molten salt, typically a eutectic mixture of fluoride salts, such as FLiBe.
  - In a typical MSR, the coolant is also used as a matrix in which the fissile material is dissolved.

PRESSURIZED WATER REACTOR

- This reactor employs Light Water (H_2O) both as coolant and a moderator and, hence, uses enriched uranium as the nuclear fuel.
- This reactor is designed to prevent the boiling of water coolant in the uranium core.
- This is achieved with the help of a pump, which circulates water coming out from the heat exchanger at a high pressure (100 to 130 atm) round the core, so that the water in the liquid state absorbs heat from the nuclear fuel and transfers it to secondary loop (the boiler)
- The pressure in the water system is maintained by a pressurised tank.
- The water, since it comes in contact with the nuclear fuel, becomes radioactive. Therefore, the entire primary circuit including the boiler circuit, must be shielded for safety reasons.

PRESSURIZED WATER REACTOR



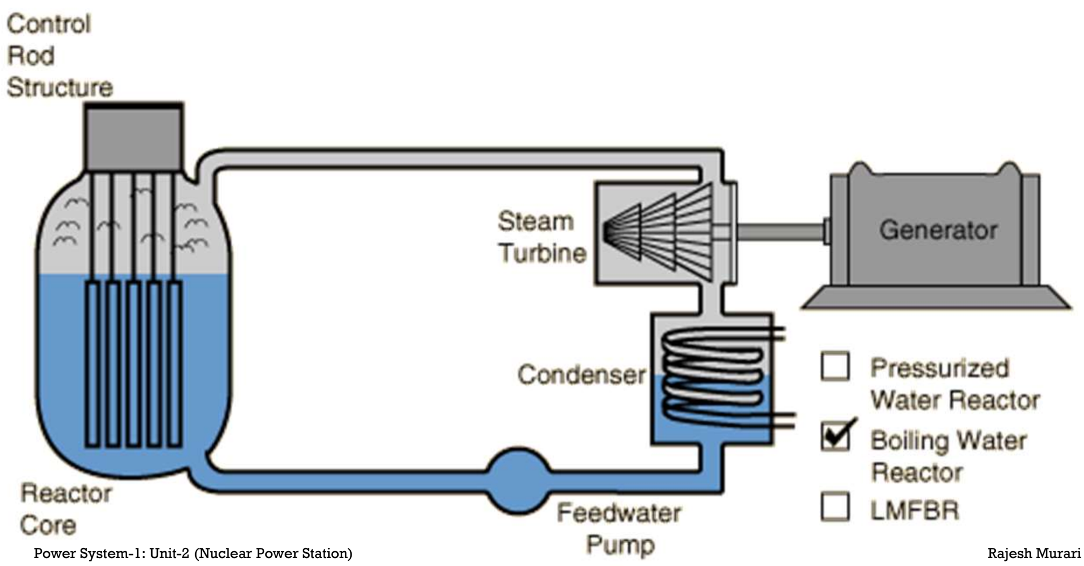
PRESSURIZED WATER REACTOR

- **Advantages:**
  - The reactor is compact in size, as enriched uranium is the fuel.
  - Water, used as coolant and moderator, is cheap and abundantly available
  - Requires smaller number of control rods. About 60 control rods for 1000MW capacity reactor.
  - Due to the separation of primary and secondary circuits, the maintenance job is easier and steam will not be contaminated by radiation.
- **Disadvantages:**
  - For recharging the core, the plant has to be shut down for a couple of months.
  - As the pressure in the primary circuit is high, high pressure vessels are required which result in high cost.
  - The thermodynamic efficiency of this plant is low (about 20%) due to low pressure in the secondary circuit.

BOILING WATER REACTOR

- This reactor employs water as the coolant, moderator and reflector and the fuel used is enriched uranium.
- The uranium elements are arranged in a particular lattice form inside a pressure vessel, which contains water.
- The nuclear heat released during the nuclear fission is absorbed by the water and steam is generated within the vessel itself.
- Feed water is made to flow from below the reactor tank, up through the fuel elements in the core, as coolant and also as a moderator.

BOILING WATER REACTOR



BOILING WATER REACTOR

- **Advantages:**
  - Since the pressure inside the vessel is small as compared to the one in PWR, the cost of the vessel is relatively less.
  - Cost of the reactor is much less as it does not require boiler, pressurizer, and circulating pump.
  - Thermal efficiency of this plant (about 30%) is higher than PWR (about 20%)
- **Disadvantages:**
  - The steam leaving this reactor is radioactive and hence shielding of the turbine and piping circuitry is essential
  - The power density of this reactor is nearly 50% of PWR and hence the size of the vessel for the same capacity of plant is more.

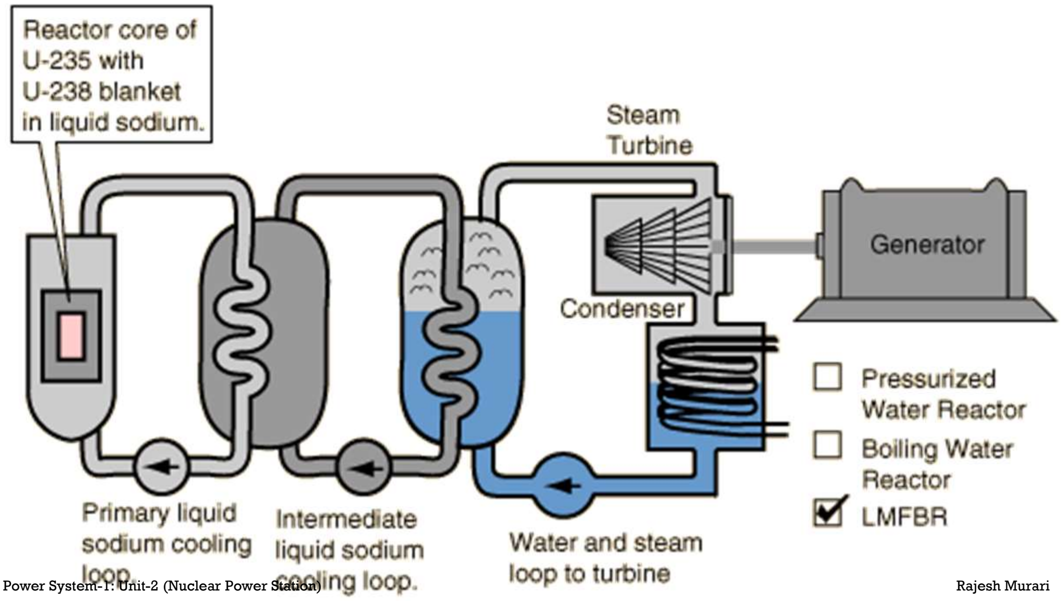
FAST BREEDER REACTOR

- The availability of natural uranium is 0.7% and remaining is ^{238}U.
- A breeder reactor which produces electricity can also produce ^{239}Pu from ^{238}U and, ^{233}U from ^{232}Th.
- Fast breeder reactors can convert more material from fertile to fissile with net fuel consumption for such reaction is much less.
- Thus, more fissile material could be produced than consumed by it.

FAST BREEDER: LIQUID METAL COOLED

- This reactor employs graphite as moderator and sodium as coolant and the fuel used is slightly enriched uranium.
- In order to have higher efficiency the temperature should be high.
- It is possible to have high temperature (about 540°C) with liquid metals at comparatively low pressure (about 7kg/cm^2) because of the excellent heat transfer capacity of these liquids when used as coolants.
- An intermediated heat exchanger using liquid Na-K is employed in between the reactor and the boiler.

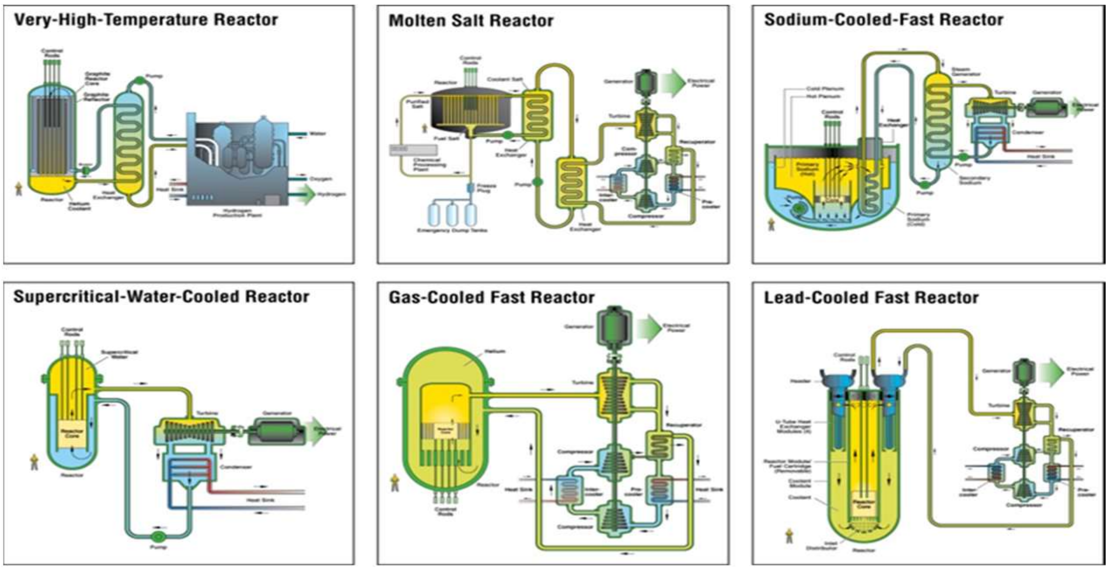
FAST BREEDER: LIQUID METAL COOLED



FAST BREEDER: LIQUID METAL COOLED

- **Advantages:**
  - High thermal efficiency can be obtained as higher temperatures as possible.
  - The reactor size is comparatively small.
  - Pressure in the vessel is low as sodium need not be pressurized.
- **Disadvantages:**
  - In case of leakage of sodium, it may result in health hazard, as it comes out in highly radioactive.
  - The primary and secondary cooling circuits should be shielded as sodium becomes highly radioactive due to neutron bombardment.

FAST BREEDER (DIFFERENT TYPES)



ADITYA COLLEGE OF ENGINEERING AND TECHNOLOGY

NUCLEAR POWER STATIONS

54

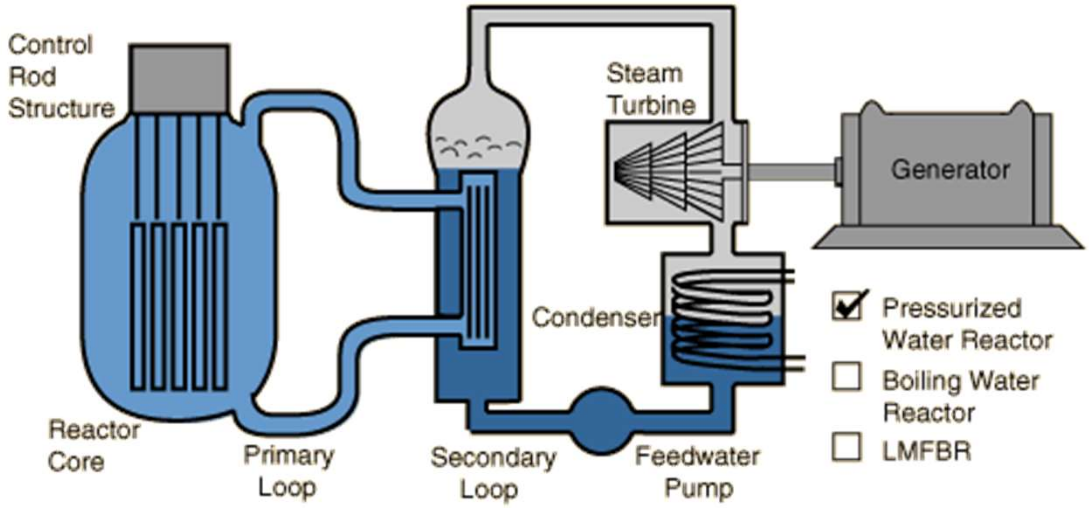
Unit-II

Power Systems -I

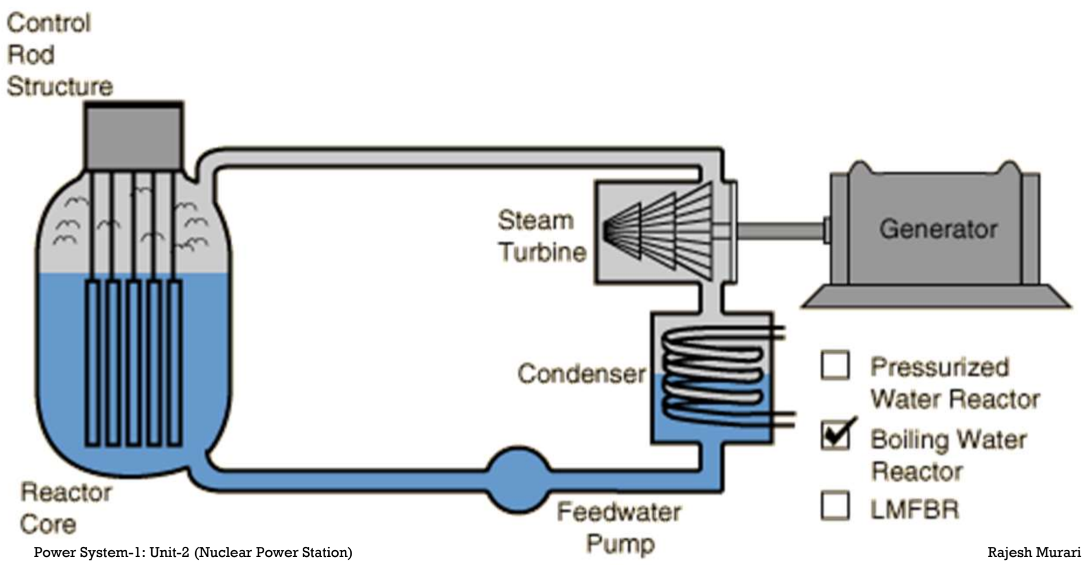
B. Tech (II Year, II Semester)

Electrical & Electronics Engineering

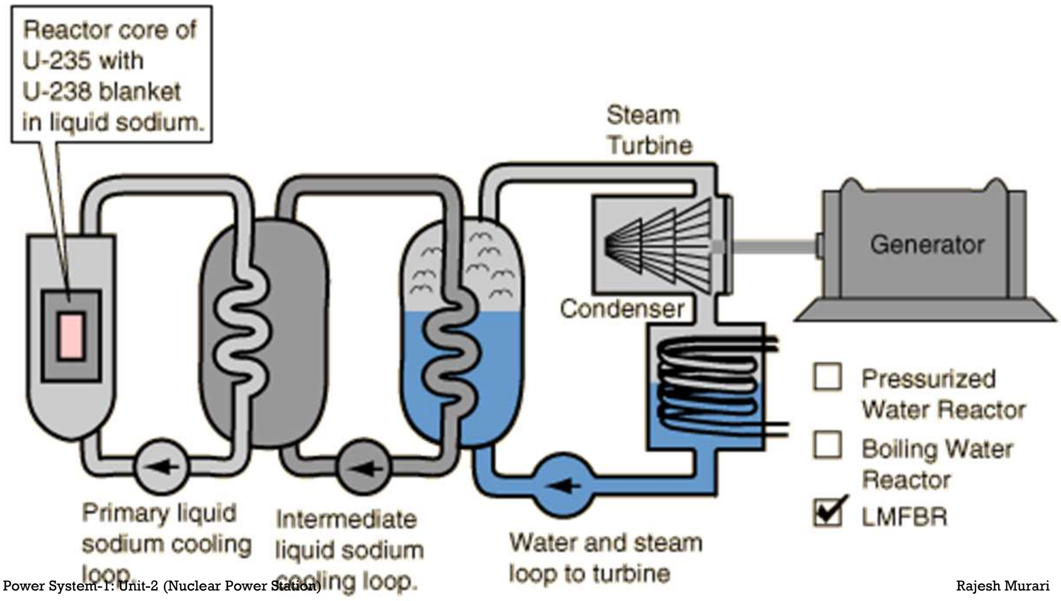
PRESSURIZED WATER REACTOR



BOILING WATER REACTOR



FAST BREEDER: LIQUID METAL COOLED



CANDU REACTOR

- CANDU (Canadian Deuterium Uranium) reactor employs heavy water as moderator and coolant and the fuel used is natural uranium.
- It has pressure tube construction and permits on-line refueling.
- It works similar to PWR, where heavy water is the primary liquid which carries the heat from the reactor to heat exchanger.
- The power output can be varied by varying the level of moderator in the reactor and hence, control rod are not required.
- The plant can be shutdown by dumping the moderator into the tank

CANDU REACTOR

- **Advantages:**
  - Natural uranium can be used
  - No control rods are required.
  - The moderator can be kept at low temperature there by its effectiveness in slowing down the neutron is increased.
  - The construction of the plant take less time capered to PWR or BWR
- **Disadvantages:**
  - High cost of heavy water.
  - The power density is low as compared to PWR and BWR, therefore the reactor size is large.
  - Design, manufacture and maintenance are complex.

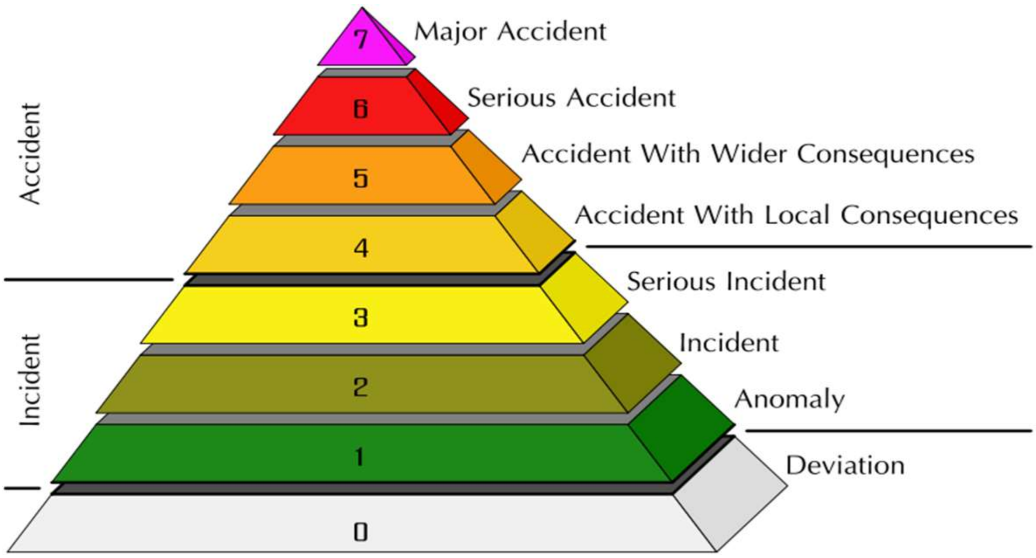
LOCATION OF NUCLEAR POWER PLANT

- **Following factors should be considered:**
  - Proximity to load center
  - Availability of cooling water
  - Radioactive waste disposal
  - Accessibility

(DIS)ADVANTAGES OF NUCLEAR POWER STATION

- **Advantages:**
  - The amount of the fuel required is quite small. Therefore, there is a considerable saving in the cost of fuel transportation
  - It requires less space
  - Low running charges for bulk power generation
  - Can be located near the load centers as it does not require large quantities of water
  - Large amounts of fuels are available. Therefore, they ensure continued supply of electrical energy for thousands of years.
- **Disadvantages:**
  - The fuel used is expensive and is difficult to recover
  - Capital cost is very high
  - Construction and commissioning of the plant requires greater technical know-how
  - Fission by-products are generally radioactive and may cause radio active pollution

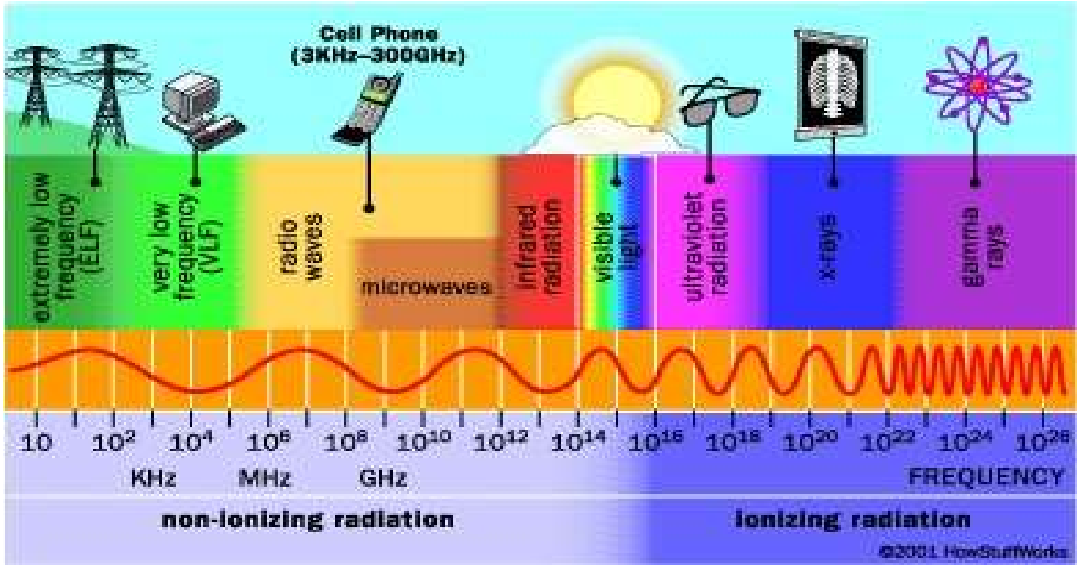
INTERNATIONAL NUCLEAR AND RADIOLOGICAL EVENT SCALE (INES)



NUCLEAR ACCIDENTS

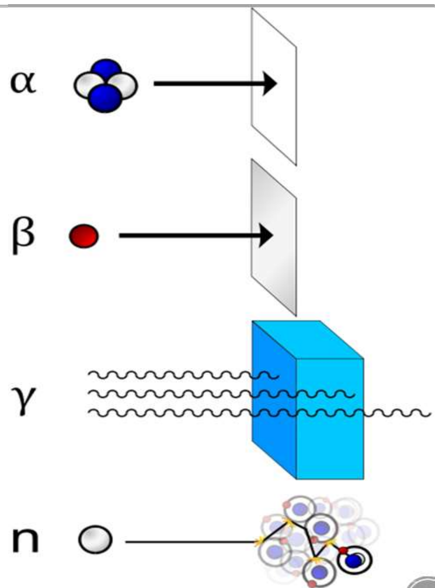
S.No.	Date	Location	Description of Incident	Dead	Cost	INES Level
1	29-Sep-57	Mayak, Kyshtym, Russia	The Kyshtym Nuclear disaster was a radiation contamination incident that occurred at Mayak, a Nuclear fuel reprocessing plant in the Soviet Union.		$US millions	6
2	22-Feb-77	Jaslovské Bohunice, Czechoslovakia	Severe corrosion of reactor and release of radioactivity into the plant area, necessitating total decommission	0	1,700	4
3	28-Mar-79	Three Mile Island, Pennsylvania, USA	Loss of coolant and partial core meltdown due to operator errors. There is a small release of radioactive gases. See also Three Mile Island accident health effects.	0	2,400	5
4	9-Mar-85	Athens, Alabama, USA	Instrumentation systems malfunction during start-up, which led to suspension of operations at all three Browns Ferry Units	0	1,830	
5	11-Apr-86	Plymouth, Massachusetts, USA	Recurring equipment problems force emergency shutdown of Boston Edison's Pilgrim Nuclear Power Plant	0	1,001	
6	26-Apr-86	Chernobyl disaster, Ukrainian USSR	Overheating, steam explosion, fire, and meltdown, necessitating the evacuation of 300,000 people from Chernobyl and dispersing radioactive material across Europe (see Chernobyl disaster effects)	56 direct; 4,000 to 985000 cancer	6,700	7
7	9-Aug-04	Fukui Prefecture, Japan	Steam explosion at Mihama Nuclear Power Plant kills 4 workers and injures 7 more	4	9	1
8	12-Mar-11	Fukushima, Japan	A tsunami flooded and damaged the 5 active reactor plants drowning two workers. Loss of backup electrical power led to overheating, meltdowns, and evacuations.[24] One man died suddenly while carrying equipment during the clean-up.	2+		7

RADIATION HAZARDS AND SHIELDING



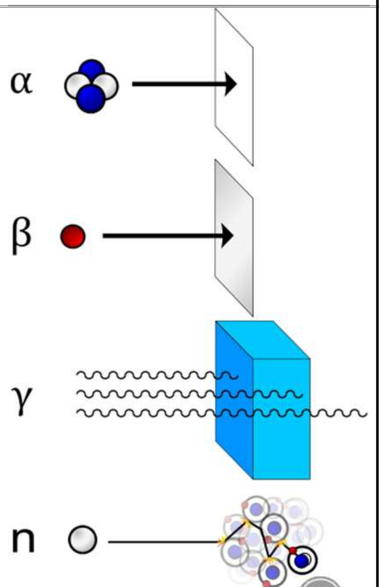
RADIATION HAZARDS

- Impacts on Human Health
  - Radiation is a mutagen, which eventually can lead to cancer.
  - Radiation can either kill cells or damage the DNA within them, which damages their ability to reproduce and can eventually lead to cancer.
  - When radiation is present, high energy particles pass through your body. These can collide with atoms in your body and disrupt atomic structure.
  - Atoms make up your DNA, so over time, your DNA can be damaged.
  - Often, it is the replication mechanisms of cells that is damaged, so uncontrolled cell division occurs- which is the definition of cancer.



SHIELDING

- α and β radiations do not cause much concern as the shielding provided will be sufficient to stop these radiations. (Single paper for α - radiation and low density materials like plastic, wood, water etc., for β - radiation)
- Fission and subsequent radioactive decay produce neutrons and gamma rays, both of which are highly penetrating radiations.
- A reactor must have specifically designed **shielding** around it to absorb and reflect this radiation in order to protect technicians and other reactor personnel from exposure.
- Concrete is the most commonly used shielding material.



NUCLEAR OR RADIO ACTIVE WASTE

- **Radioactive waste** is waste that contains radioactive material.
- Radioactive waste is usually a by-product of nuclear power generation and other applications of nuclear fission or technology, such as research and medicine.
- Radioactive waste is hazardous to most forms of life and the environment, and is regulated by government agencies in order to protect human health and the environment.

NUCLEAR OR RADIO ACTIVE WASTE

- It is broadly classified into low-level waste (LLW), such as paper, rags, tools, clothing, which contain small amounts of mostly short-lived radioactivity,
- Intermediate-level waste (ILW), which contains higher amounts of radioactivity and requires some shielding, and
- High-level waste (HLW), which is highly radioactive and hot due to decay heat, so requires cooling and shielding.

COMMON RADIOACTIVE ISOTOPES PRODUCED DURING NUCLEAR REACTIONS

Isotope	Half-life	Isotope	Half-life	Isotope	Half-life
Relatively short half-life					
Strontium-89	54 days	Zirconium-95	65 days	Niobium-95	39 days
Ruthenium-103	40 days	Rhodium-103	57 minutes	Rhodium-106	30 seconds
Iodine-131	8 days	Xenon-133	8 days	Tellurium-134	42 minutes
Barium-140	13 days	Lanthanum-140	40 h	Cerium-141	32 days
*Year to century-scale half-life**					
Hydrogen-3	12 years	Krypton-85	10 years	Strontium-90	29 years
Ruthenium-106	1 year	Cesium-137	30 years	Cerium-144	1.3 years
Promethium-147	2.3 years	Plutonium-238	85.3 years	Americium-241	440 years
Curium-224	17.4 years				
Longer half-life					
Technecium-99	2×10^6 years	Iodine-129	1.7×10^7 years	Plutonium-239	24000 years
Plutonium-240	6500 years	Americium-243	7300 years		

*Half-lives of the order of years to decades of isotopes of elements that can seek tissues or organs biologically (being akin to other elements chemically) are the most hazardous from point of view of radiation. For example, ^{90}Sr, being chemically akin to Ca, can seek the bone and lodge itself there for years causing radioactive damage to surrounding tissues.

NUCLEAR WASTE DISPOSAL

- Radioactive waste management involves minimizing radioactive residues, handling waste-packing safely, storage and safe disposal in addition to keeping sites of origin of radioactivity clean.
- Poor practices lead to future problems. Hence choice of sites where radioactivity is to be managed safely is equally important in addition to technical expertise and finance, to result in safe and environmentally sound solutions.

NUCLEAR WASTE DISPOSAL

- The International Atomic Energy Agency (IAEA) is promoting acceptance of some basic tenets by all countries for radioactive waste management.
- These include:
  1. Securing acceptable level of protection of human health;
  2. Provision of an acceptable level of protection of environment;
  3. Assurance of negligible effects beyond national boundaries;
  4. Acceptable impact on future generations; and
  5. No undue burden on future generations.
- There are other legal, control, generation, safety and management aspects also

NUCLEAR OR RADIO ACTIVE WASTE

- In nuclear reprocessing plants about 96% of spent nuclear fuel is recycled back into uranium-based and mixed-oxide fuels.
- The residual 4% is fission products which are highly radioactive High Level Waste.
- This radioactivity naturally decreases over time, so the material is stored in appropriate disposal facilities for a sufficient period until it no longer poses a threat.
- The time radioactive waste must be stored for depends on the type of waste and radioactive isotopes.
- Short-term approaches to radioactive waste storage have been segregation and storage on the surface or near-surface.
- Burial in a deep geological repository is a favored solution for long-term storage of high-level waste, while re-use and transmutation are favored solutions for reducing the HLW inventory.

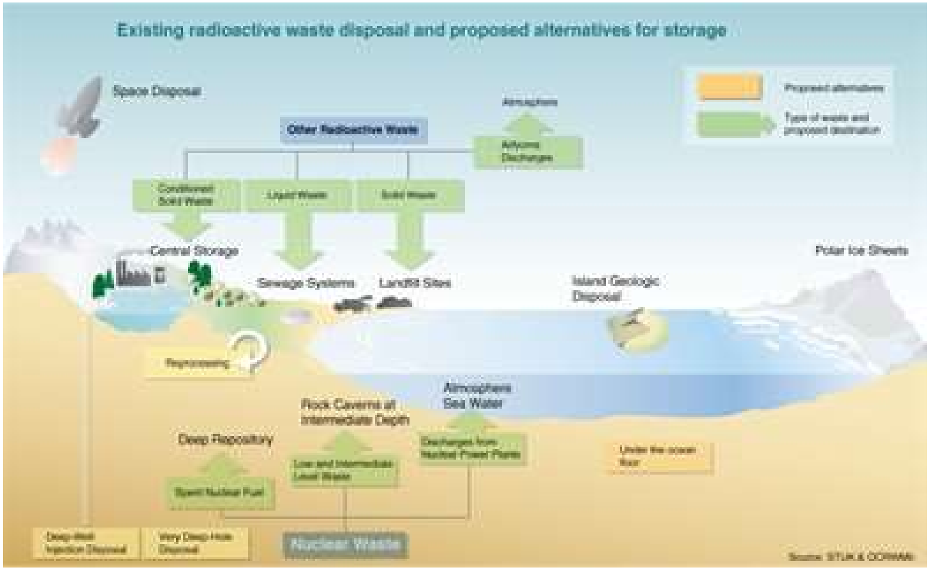
NUCLEAR WASTE DISPOSAL

- The following options have been aired sometime or the other.
- Each one of the options demands serious studies and technical assessments:
  - Deep geological repositories
  - Ocean dumping
  - Seabed burial
  - Sub-seabed disposal
  - Subductive waste disposal method
  - Transforming radioactive waste to non-radioactive stable waste
  - Dispatching to the Sun.

NUCLEAR WASTE DISPOSAL

Ideas	Examples
Long-term above ground storage	• Investigated in France, Netherlands, Switzerland, UK, and USA. • Not currently planned to be implemented anywhere.
Disposal in outer space (proposed for wastes that are highly concentrated)	• Investigated by USA. • Investigations now abandoned due to cost and potential risks of launch failure.
Rock-melting (proposed for wastes that are heat-generating)	• Investigated by Russia, UK, and USA. • Not implemented anywhere. • Laboratory studies performed in the UK.
Disposal at subduction zones	• Investigated by USA. • Not implemented anywhere. • Not permitted by international agreements.
Sea disposal	• Implemented by Belgium, France, Germany, Italy, Japan, Netherlands, Russia, South Korea, Switzerland, UK, and USA. • Not permitted by international agreements.
Sub seabed disposal	• Investigated by Sweden and UK (and organisations such as the OECD Nuclear Energy Agency). • Not implemented anywhere. • Not permitted by international agreements.
Disposal in ice sheets (proposed for wastes that are heat-generating)	• Investigated by USA. • Rejected by countries that have signed the Antarctic Treaty or committed to providing solutions within national boundaries.
Deep well injection (for liquid wastes)	• Implemented in Russia for many years for LLW and ILW. • Investigations abandoned in the USA in favour of deep geological disposal of wastes in solid form.

NUCLEAR WASTE DISPOSAL



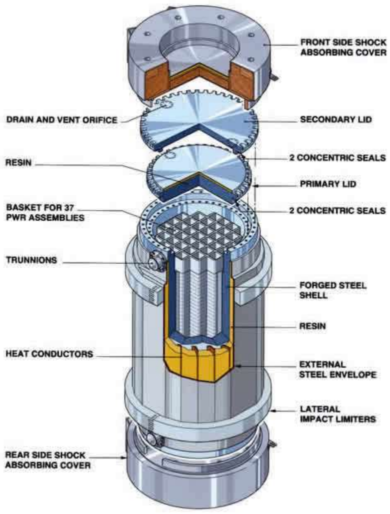
NUCLEAR WASTE DISPOSAL

Storage pond for used fuel at the Thermal Oxide Reprocessing Plant (Thorp) at the UK's Sellafield site (Sellafield Ltd).

NUCLEAR WASTE DISPOSAL

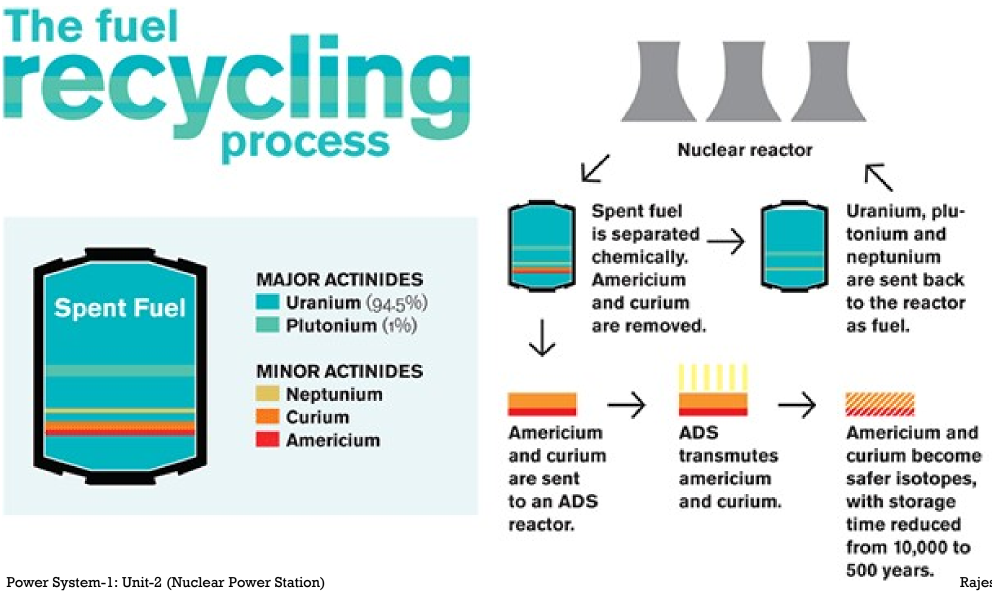
Water-filled storage pools at the Central Interim Storage Facility for Spent Nuclear Fuel (CLAB) facility in Sweden.

NUCLEAR WASTE DISPOSAL



Loading silos with canisters containing vitrified HLW in the UK. Each disc on the floor covers a silo holding ten canisters.

NUCLEAR WASTE RECYCLING



ADITYA COLLEGE OF ENGINEERING AND TECHNOLOGY

SUBSTATIONS

Unit-III

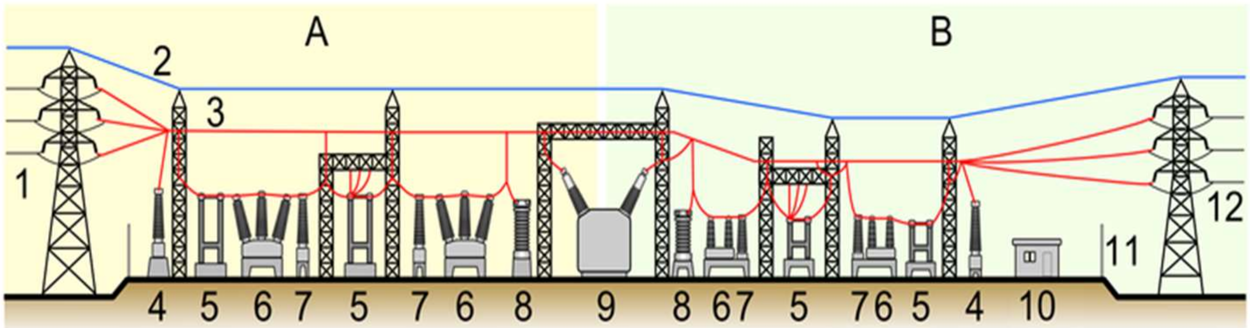
Power Systems -I

B. Tech (II Year, II Semester)

Electrical & Electronics Engineering

ADITYA

ELEMENTS OF SUBSTATION



A: Primary Power Lines' side **B:** Secondary Power Lines' side

1. Primary Power Lines **2.** Ground Wire **3.** Overhead Lines **4.** Lightning Arrester

5. Disconnect Switch **6.** Circuit Breaker **7.** Current Transformer

8. Transformer for Measurement of Voltage **9.** Main Transformer

10. Control Building **11.** Security Fence **12.** Secondary Power Lines

SUBSTATION

- Most of the substations are concerned with the changing voltage levels of the electric supply.
- Substations are to perform the following functions:
  - To switch on and off the power lines, known as switching operation
  - To transform voltage from higher to lower or vice-versa, known as voltage transformation operation
  - To convert A.C. to D.C. or vice-versa, known as power conversion
  - To improve the power factor, known as p.f. correction operation

LOCATION OF SUBSTATION

- Type of Substation
- Availability of Suitable Land:
  - 400kV Substation - 50 acres
  - 220kV Substation - 25 acres
  - 132kV Substation - 10 acres
- Should be close to Load Centre
- Provision for Voltage Regulation
- Access for incoming sub-transmission line and outgoing primary feeders
- Enough space for future expansion
- Measures to reduce service outages

CLASSIFICATION OF SUBSTATION

1. **According to SERVICE type:**
   A. Transformer Substations:
      i. Transmission or Primary: (11/33 kV to 220/400 kV)
      ii. Sub-Transmission: (step down to 11/33 kV)
      iii. Step-down or Distribution: (step down to 400V three phase or 230 V single phase)
   B. Industrial Substations:
   C. Switching Substations:
   D. Synchronous Substations:
   E. Frequency Change Substations:
   F. Power Conversion Substations:
2. **According to DESIGN:**
   A. Indoor Substation
   B. Outdoor Substation
      i. Pole mounted
      ii. On Foundation

CLASSIFICATION OF SUBSTATION

1. **According to NATURE of DUTIES:**
   A. Step-Up or Primary Substations:
      Generated voltage levels are very low (3.3, 6.6, 11, upto 33kV)
   B. Primary Grid Substations:
   C. Step-Down or Distribution or Secondary Substations:
2. **According to SERVICE type:**
   A. Transformer Substations:
   B. Switching Substations:
   C. Converting Substations:

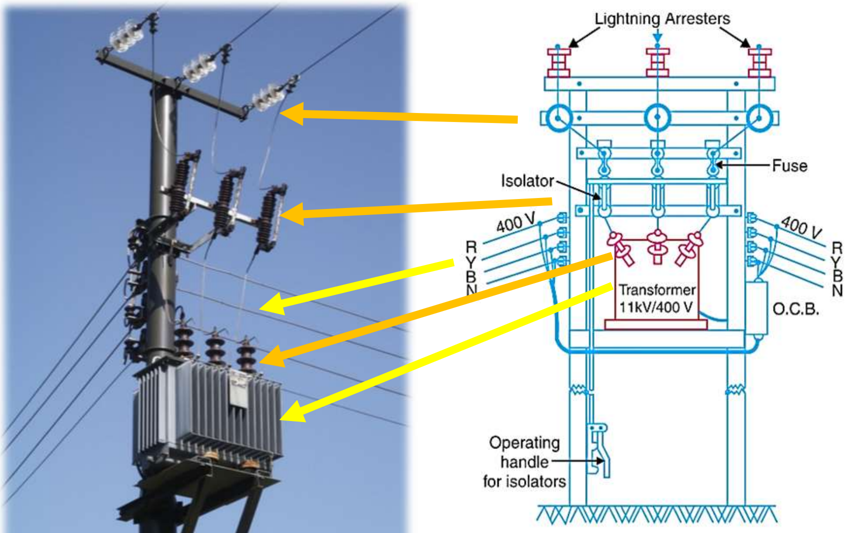
CLASSIFICATION OF SUBSTATION

1. **According to OPERATING VOLTAGE:**
   A. High Voltage (HV) Substations: (11kV to 66kV)
   B. Extra High Voltage (EHV) Substations: (132kV and 400kV)
   C. Ultra High Voltage (UHV) Substations: (400kV and above)
2. **According to IMPORTANCE:**
   A. Grid Substations:
   B. Town Substations: (33/11kV)
3. **According to DESIGN:**
   A. Indoor Substation: (upto 33kV; in case of GIS - upto EHV)
   B. Outdoor Substation:
      i. Pole mounted: (Single Stout, or H-pole and 4-pole; 25 to 125 kVA)
      ii. On Foundation: (above 250kVA; 33kV and above)

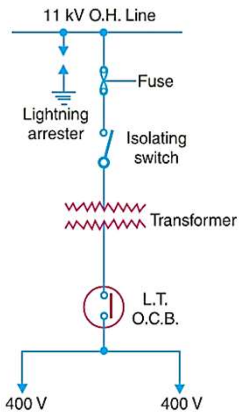
RATING OF SUBSTATION

- **Rating of the substation depends on the following factors:**
  - Nature of the load connected
  - Load density of the area feeder
  - Rate of load growth
  - Type of design and equipment of substation
  - Quality of the service to be provided
  - Number of outgoing feeders
  - Voltage levels of primary feeders

Pole Mounted SUBSTATION



(i)



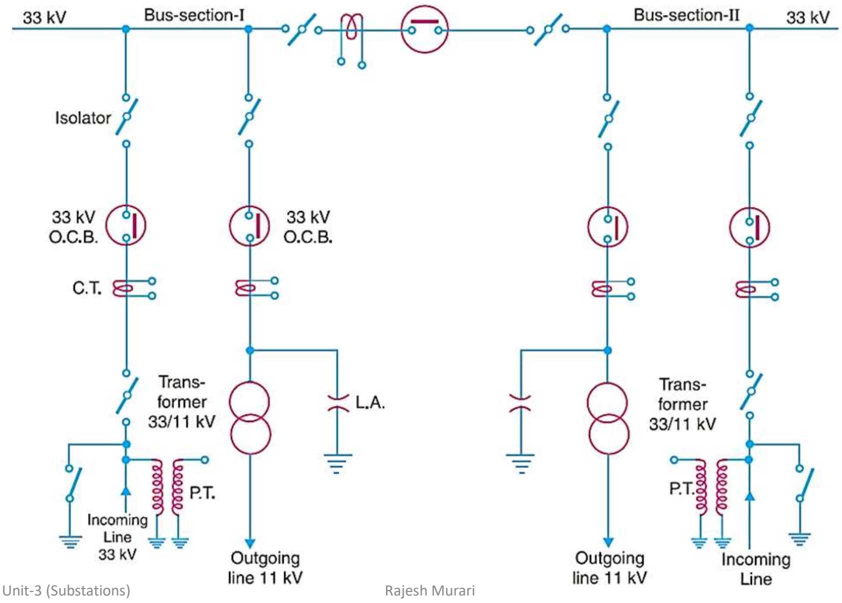
(ii)

Indoor vs. Outdoor SUBSTATIONs

S.No.	Particular	Outdoor Sub-station	Indoor Sub-station
1	Space required	More	Less
2	Time required for erection	Less	More
3	Future extension	Easy	Difficult
4	Fault location	Easier beacuse the equipment is in full view	Difficult because the equipment is enclosed
5	Capital cost	Low	High
6	Operation	Difficult	Easier
7	Possibility of fault escalation	Less because greater clearances can be provided	More

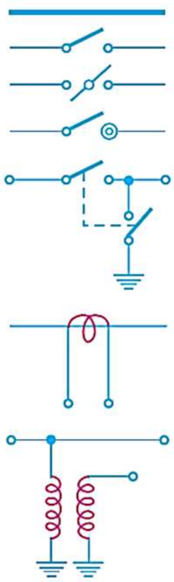
Most of the substations are of outdoor type. Indoor type are constructed only where outdoor type is impractical or prohibited by law.

33/11kV Substation Layout



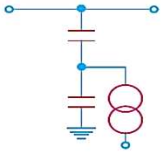
Symbols of Equipment in Substation

1 Bus-bar
2 Single-break isolating switch
3 Double-break isolating switch
4 On load isolating switch
5 Isolating switch with earth Blade
6 Current transformer
7 Potential transformer

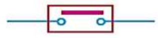


Symbols of Equipment in Substation

8 Capacitive voltage transformer

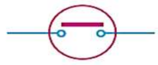


9 Oil circuit breaker

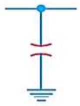


10 Air circuit breaker with overcurrent tripping device

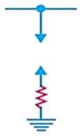
11 Air blast circuit breaker



12 Lightning arrester (active gap)



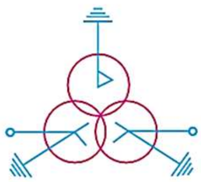
13 Lightning arrester (valve type)



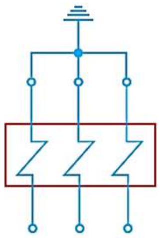
Symbols of Equipment in Substation

14 Arcing horn

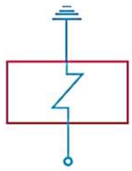
15 3-ϕ Power transformer



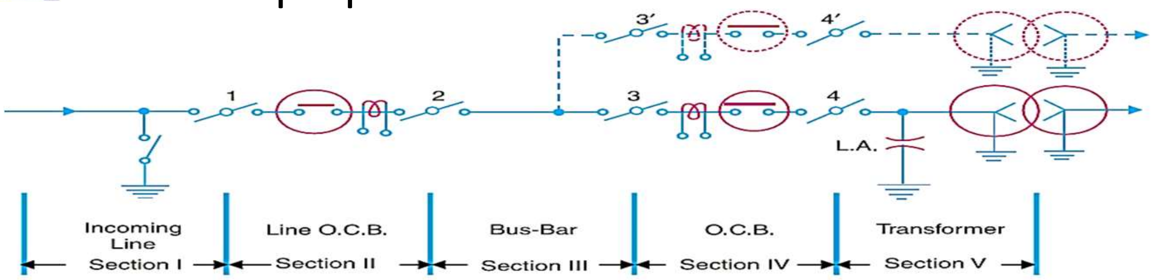
16 Overcurrent relay



17 Earth fault relay



Equipment in Substation



1. **Bus-Bar**
   a. **Single Bus-Bar Arrangement**
   b. **Single Bus-Bar Arrangement with Sectionalizer**
   c. **Double Bus-Bar Arrangement**
2. **Insulator**
3. **Isolating Switches**
4. **Circuit Breaker**
5. **Power Transformer**
6. **Instrument Transformer**
   a. **Current Transformer**
   b. **Voltage or Potential Transformer**
7. **Metering and Indicating Instruments**
8. **Miscellaneous Equipment**
   a. **Fuses**
   b. **Carrier – Current Equipment**
   c. **Substation Auxiliary Supplies**

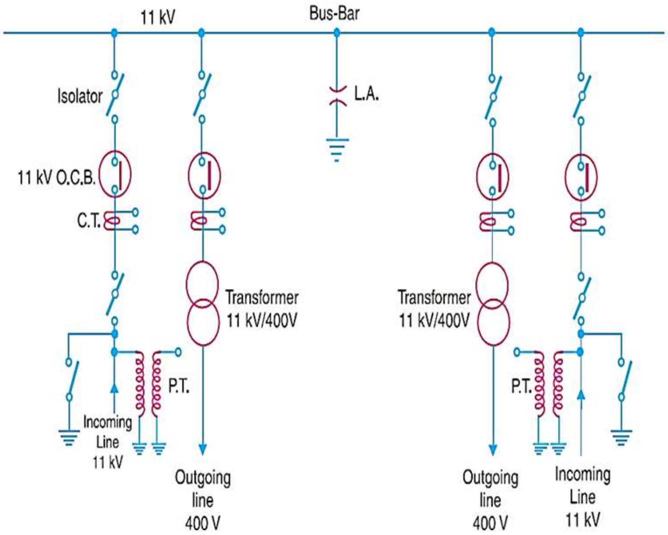
1. BUS-BARS

- **Bus-bars are the important components in a sub-station.**
- **When a number of lines operating at the same voltage have to be directly connected electrically, bus-bars are used as the common electrical component. Bus-bars are copper or aluminium bars (generally of rectangular x-section) and operate at constant voltage.**
- **The incoming and outgoing lines in a sub-station are connected to the bus-bars.**
- **There are several bus-bar arrangements that can be used in a sub-station. The choice of a particular arrangement depends upon various factors such as system voltage, position of sub-station, degree of reliability, cost etc.**
- **The most commonly used bus-bar arrangements in sub-stations are :**
  a. **Single bus-bar arrangement**
  b. **Single bus-bar system with sectionalisation**
  c. **Double bus-bar arrangement**

1. BUS-BARS

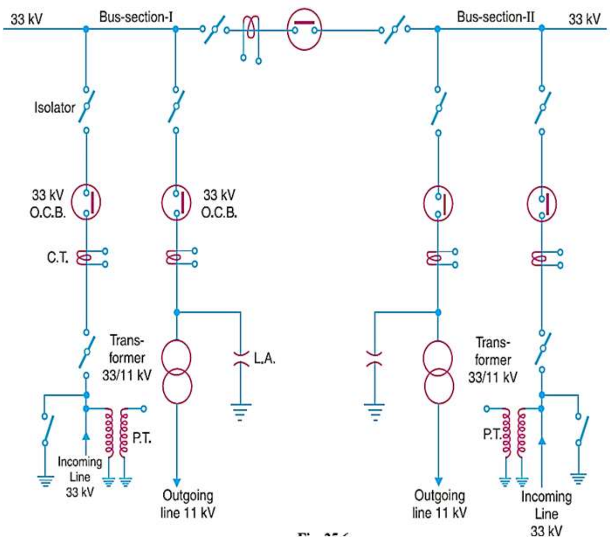
1. BUS-BARS

a. Single Bus-Bar System



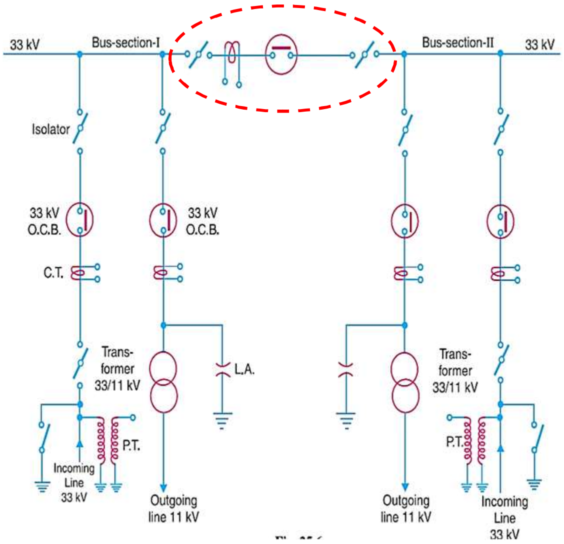
- Simplest design, having relatively a few outgoing and incoming feeders and distributers.
- This arrangement is not used for voltages exceeding 33kV. Often used 11kV indoor sub-stations.
- **Advantages:**
  - Low initial cost
  - Less maintenance
  - Simple operation
- **Disadvantages:**
  - The bus-bar cannot be cleaned, repaired or tested without de-energizing the whole system.
  - If fault occurs on the bus-bar, complete interruption of supply.
  - Any fault on the system is fed by all generating capacity, resulting in very large fault current.

b. Single Bus-Bar System with Sectionalizer

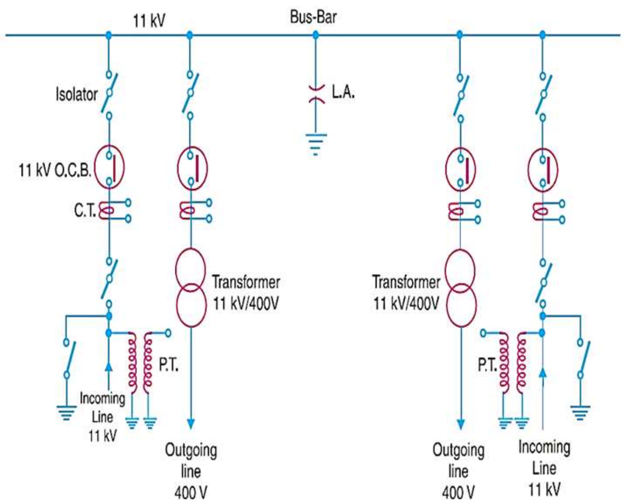


- In this arrangement, the single bus-bar is divided into sections and load is equally distributed on all the sections.
- Any two sections of the bus-bar are connected by a circuit breaker and isolators.
- This arrangement is used for voltages upto 33 kV.
- **Advantages:**
  - If a fault occurs on any section of the bus, that section can be isolated without affecting the supply from other sections.
  - Repairs and maintenance of any section of the bus-bar can be carried out by de-energising that section only, eliminating the possibility of complete shutdown.

b. Single Bus-Bar System with Sectionalizer

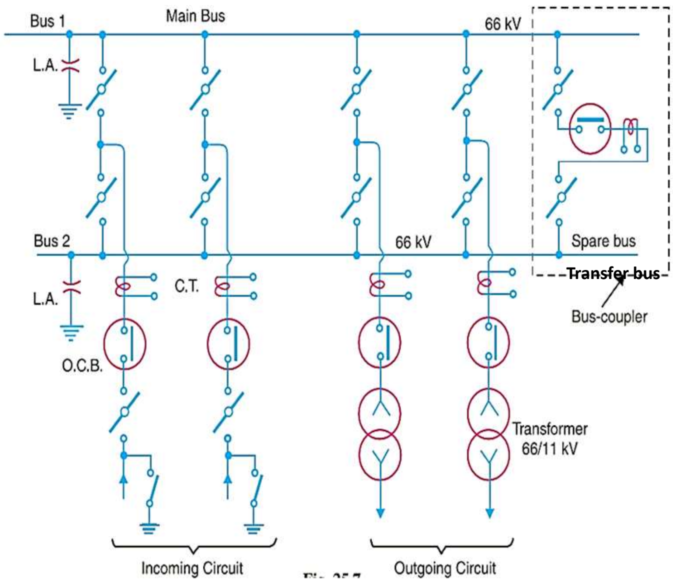


Single Bus-Bar System with Sectionalizer



Single Bus-Bar System without Sectionalizer

c. Double Bus-Bar System



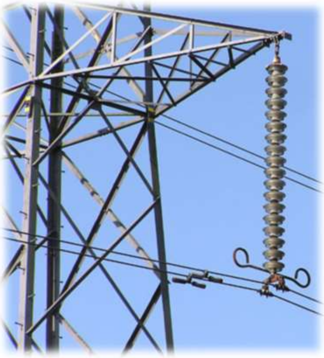
- This system consists of two bus-bars, a **"main" bus-bar and a "spare" bus-bar or "transfer" bus-bar**. Each bus-bar has the capacity to take up the entire sub-station load.
- The incoming and outgoing lines can be connected to either bus-bar with the help of a bus-bar coupler which consists of a circuit breaker and isolators.
- For above 33kV, this system is used.
- **Advantages:**
  - Repairs and maintenance on main bus-bar can be carried out by transferring entire load to spare busbar.
  - If fault occurs on busbar, continuity of supply can be maintained by transferring it to other busbar
- **Disadvantages:**
  - Too expensive
  - Service is interrupted during switching between busbars

2. Insulators


Cap and pin type suspension


Cap and pin type suspension


Pin type insulator BS P-11-Y



- **The insulators serve two purposes. They support the conductors (or bus-bars) and confine the current to the conductors.**
- **The most commonly used material for the manufacture of insulators is porcelain.**
- **There are several types of insulators (e.g. pin type, suspension type, post insulator etc.) and their use in the sub-station will depend upon the service requirement.**
- **For ex-ample, post insulator is used for bus-bars. A post insulator consists of a porcelain body, cast iron cap and flanged cast iron base.**
- **The hole in the cap is threaded so that bus-bars can be directly bolted to the cap.**

3. Isolator Switches

- **In sub-stations, it is often desired to disconnect a part of the system for general maintenance and repairs.**
- **This is accomplished by an isolating switch or isolator.**
- **An isolator is essentially a knife switch and is designed to open a circuit under no load.**
- **In other words, isolator switches are operated only when the lines in which they are connected carry no current.**

4. Circuit Breaker

- A circuit breaker is an equipment which can open or close a circuit under normal as well as fault conditions.
- It is so designed that it can be operated manually (or by remote control) under normal conditions and automatically under fault conditions.
- For the latter operation, a relay circuit is used with a circuit breaker.
- Generally, bulk oil circuit breakers are used for voltages upto 66kV while for high (>66 kV) voltages, low oil circuit breakers are used.
- For still higher voltages, air-blast, vacuum or SF_6 circuit breakers are used.

5. Power Transformer

- A power transformer is used in a sub-station to step-up or step-down the voltage.
- Except at the power generation station, all the subsequent sub-stations use step-down transformers to gradually reduce the voltage of electric supply and finally deliver it at utilisation voltage.
- The use of 3-phase transformer permits two advantages:
  1. only one 3-phase load-tap changing mechanism can be used.
  2. its installation is much simpler than the three single phase transformers

6. Instrument Transformers

- The lines in sub-stations operate at high voltages and carry current of thousands of amperes.
- The measuring instruments and protective devices are designed for low voltages (generally 110 V) and currents (about 5 A).
- Therefore, they will not work satisfactorily if mounted directly on the power lines. This difficulty is overcome by installing instrument transformers on the power lines.
- The function of these instrument transformers is to transfer voltages or currents in the power lines to values which are convenient for the operation of measuring instruments and relays.
- Types of instrument transformers:
  - Current transformer (C.T.)
  - Potential transformer (P.T.)

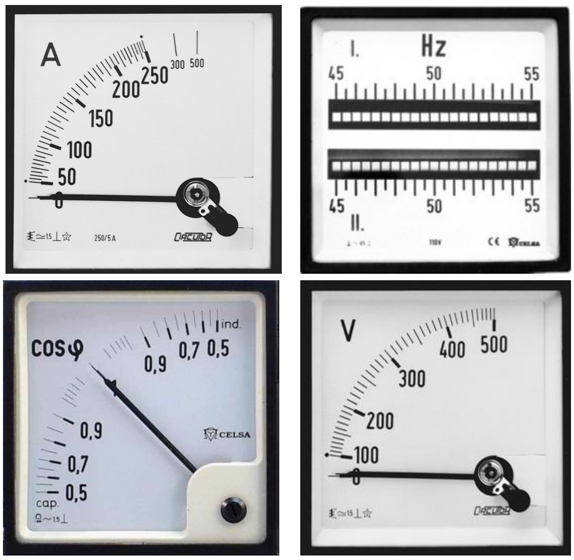
6(a). Current Transformers (C.T.)

- A current transformer in essentially a step-up transformer which steps down the current to a known ratio.
- The primary of this transformer consists of one or more turns of thick wire connected in series with the line.
- The secondary consists of a large number of turns of fine wire and provides for the measuring instruments and relays a current which is a constant fraction of the current in the line.
- Suppose a current transformer rated at 100/5 A is connected in the line to measure current. If the current in the line is 100 A, then current in the secondary will be 5A.
- Similarly, if current in the line is 50A, then secondary of C.T. will have a current of 2·5 A. Thus the C.T. under consideration will step down the line current by a factor of 20.

6(b). Potential Transformers (P.T.)

- **It is essentially a step down transformer and steps down the voltage to a known ratio.**
- **The primary of this transformer consists of a large number of turns of fine wire connected across the line.**
- **The secondary winding consists of a few turns and provides for measuring instruments and relays a voltage which is a known fraction of the line voltage.**
- **Suppose a potential transformer rated at 66kV/110V is connected to a power line.**
- **If line voltage is 66kV, then voltage across the secondary will be 110 V.**

7. Metering & Indicating Instruments



- **There are several metering and indicating instruments (e.g. ammeters, voltmeters, energy meters etc.) installed in a sub-station to maintain watch over the circuit quantities.**
- **The instrument transformers are invariably used with them for satisfactory operation.**

8. Miscellaneous Equipment

- **In addition to above, there may be following equipment in a sub-station :**
  - **fuses**
  - **carrier-current equipment**
  - **sub-station auxiliary supplies**

(DIS) ADVANTAGES of AIS

Advantages of AIS (Air Insulated Substation):

- Air used as a dielectric.
- Normally used for outdoor substations.
- In very few cases used for indoor substations.
- Easy to expand (in case that space is not an issue)
- Excellent overview, simple handling and easy access.

Disadvantages of AIS:

- Large dimensions due to statutory clearances and poor dielectric strength of air.
- Insulation deterioration with ambient conditions and susceptibility to pollutants.
- Wastage of space.
- Life of steel structures degrades.
- Seismic instability.
- Large planning & execution time.
- Regular maintenance of the substation required.

GAS INSULATED SUB-STATION

(GIS)

GAS INSULATED SUBSTATION

- In GIS substation, all live components are enclosed in a grounded metal enclosure and the whole system housed in a chamber full of SF_6 (Sulphur Hexafluoride) gas.

GAS INSULATED SUBSTATION

- Sulfur hexafluoride ($SF_{6)}$ is an inert, nontoxic, colorless, odorless, tasteless, and nonflammable gas consisting of a sulfur atom surrounded by and tightly bonded to six fluorine atoms.
- SF_6 is about five times as dense as air. SF_6 is used in GIS at pressures from 400 to 600 kPa absolute. The pressure is chosen so that the SF_6 will not condense into a liquid at the lowest temperatures the equipment experiences.
- SF_6 has two to three times the insulating ability of air at the same pressure.
- SF_6 is about 100 times better than air for interrupting arcs. It is the universally used interrupting medium for high voltage circuit breakers, replacing the older mediums of oil and air.
- SF_6 decomposes in the high temperature of an electric arc, but the decomposed gas recombines back into SF_6 so well that it is not necessary to replenish the SF_6 in GIS.

Properties and Advantages of SF_6

- **Properties and Advantages of SF_6 (Sulphur Hexafluoride) gas:**
  - Maintains atomic and molecular properties even at high voltages,
  - High cooling properties,
  - Excellent arc quenching properties.
  - SF_6 is no hazardous material.
  - SF_6 has no impact for the ozonosphere.
  - The dielectric strength of SF_6 gas at atmospheric pressure is approximately three times that of air.
  - It is incombustible, non toxic, colorless and chemically inert.
  - It has arc-quenching properties 3 to 4 times better than air at equal pressure.

Need for GIS

- Non availability of sufficient space.
- Difficult climatic and seismic conditions at site.
- Urban site (high rise building).
- High altitudes.
- Limitations of AIS.

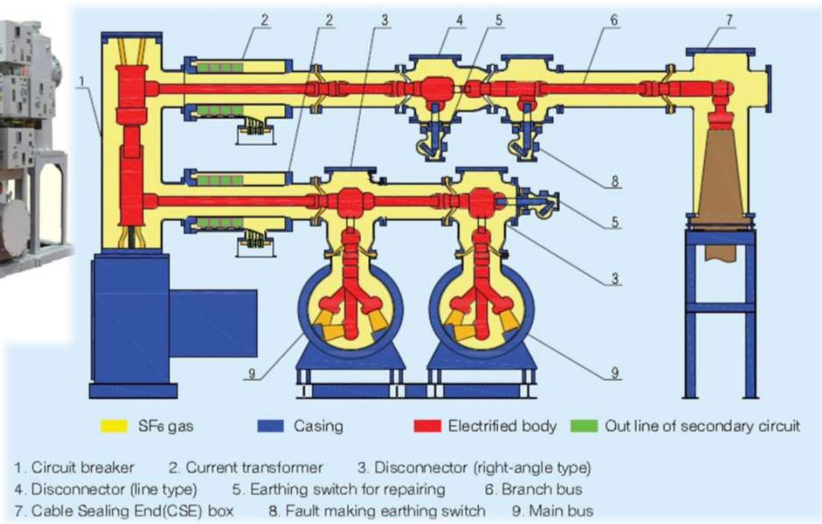
Need of GIS

- Compact, multi-component assembly.
- Enclosed in a ground metallic housing.
- Sulphur Hexafluoride (SF_6) gas the primary insulating medium.
- SF_6 gas is superior dielectric properties used at moderate pressure for phase to phase and phase to ground insulation
- Preferred for voltage ratings of 72.5 kV, 145 kV, 300 kV and 420 kV and above.
- Various equipment's like Circuit Breakers, Bus-Bars, Isolators, Load Break Switches, Current Transformers, Voltage Transformers, Earthing, Switches, etc. housed in metal enclosed modules filled with SF_6 gas.

115kV GIS

LAYOUT OF GIS

Sectional Diagram of One Bay



AIS (132kV)

GIS (132kV)

AIS VS GIS

Aspect	GIS	AIS
Media for Busbar Insulation	SF6	Air
Media for Switching	SF6 or Vacuum	Air, Oil, SF6, or Vacuum
Physical Size	Small	Large as clearance should be maintained
Sensitivity to environment/ pollution	Excellent	Moderate (Humidity, pollution effects insulation)
Maintenance	Minimal	Moderate
Safety for working personal	As the enclosure is earthed it is safe	Extremely careful as all components are exposed
Construction/Installation	Less Time (only assembling)	More time
Cost	High	Low
Fault Clearance	Difficult	Easy

GIS VS AIS


GAS
INSULATED
SUBSTATIONS USE
63% LESS
SPACE THAN
AIR
INSULATED
SUBSTATIONS

ADITYA COLLEGE OF ENGINEERING AND TECHNOLOGY

UNDERGROUND CABLES

Unit-IV

Power Systems -I

B. Tech (II Year, II Semester)

Electrical & Electronics Engineering

Introduction

- Electric power can be transmitted or distributed either by overhead system or by underground cables.
- The underground cables have several advantages such as less liable to damage through storms or lightning, low maintenance cost, less chances of faults, smaller voltage drop and better general appearance.
- However, their major drawback is that they have greater installation cost and introduce insulation problems at high voltages compared with the equivalent overhead system.
- For this reason, underground cables are employed where it is impracticable to use overhead lines.
- Such locations may be thickly populated areas where municipal authorities prohibit overhead lines for reasons of safety, or around plants and substations or where maintenance conditions do not permit the use of overhead construction.

SYLLABUS

- Types of Cables
- Construction
- Types of insulating materials
- Calculation of insulation resistance
- Stress in insulation and Power factor of cable.
- Capacitance of single and 3-Core belted Cables
- Grading of Cables
- Capacitance grading and
- Inter sheath grading

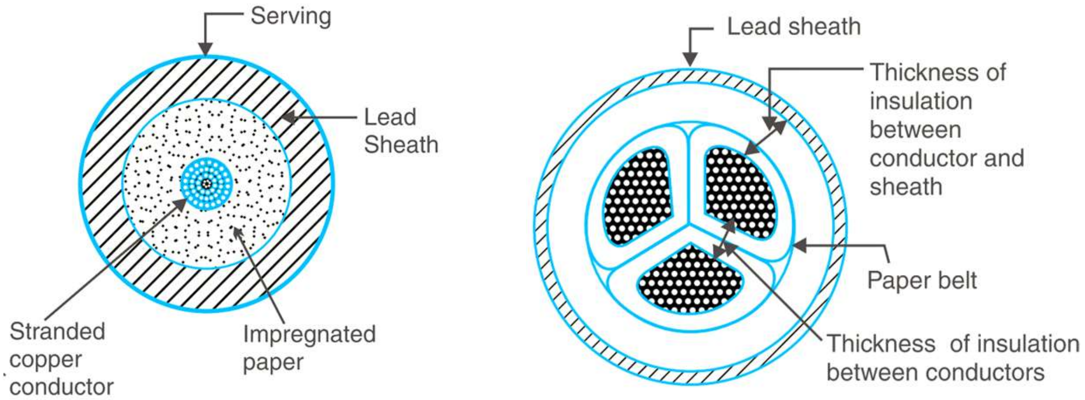
Types of Cables

- Cables for underground service may be classified in two ways according to
  - The type of insulating material used in their manufacture
  - The voltage for which they are manufactured.
- However, the latter method of classification is generally preferred, according to which cables can be divided into the following groups :
  - Low-tension (L.T.) cables — upto 1 kV
  - High-tension (H.T.) cables — upto 11 kV
  - Super-tension (S.T.) cables — from 22 kV to 33 kV
  - Extra high-tension (E.H.T.) cables — from 33 kV to 66 kV
  - Extra super voltage cables — beyond 132 kV

Types of Cables

- A cable may have one or more than one core depending upon the type of service for which it is intended. It may be
  - Single-core
  - Two-core
  - Three-core
  - Four-core etc.
- For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand.

Single-core vs. Three-core cable

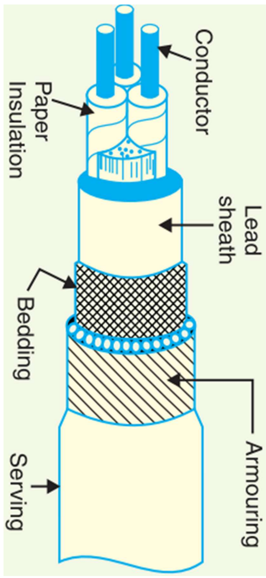


Features of Cables

- *An* **underground cable** *essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover.*
- Although several types of cables are available, the type of cable to be used will depend upon the working voltage and service requirements.
- In general, a cable must fulfil the following necessary requirements :
  - The conductor used in cables should be tinned stranded copper or aluminium of high conductivity. Stranding is done so that conductor may become flexible and carry more current.
  - The conductor size should be such that the cable carries the desired load current without overheating and causes voltage drop within permissible limits.
  - The cable must have proper thickness of insulation in order to give high degree of safety and reliability at the voltage for which it is designed.
  - The cable must be provided with suitable mechanical protection so that it may withstand the rough use in laying it.
  - The materials used in the manufacture of cables should be such that there is complete chemical and physical stability throughout.

Construction of Cables

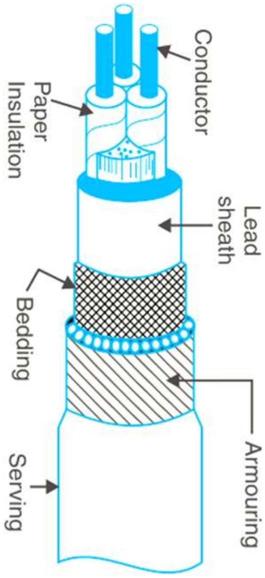
- **The various parts are :**
  - *Cores or Conductors.* A cable may have one or more than one core (conductor) depending upon the type of service for which it is intended.
  - For instance, the 3-conductor cable shown in Figure is used for 3-phase service. The conductors are made of tinned copper or aluminium and are usually stranded in order to provide flexibility to the cable.
- ***Insulation:*** Each core or conductor is provided with a suitable thickness of insulation, the thickness of layer depending upon the voltage to be withstood by the cable. The commonly used materials for insulation are impregnated paper, varnished cambric or rubber mineral compound.
- ***Metallic sheath:*** In order to protect the cable from moisture, gases or other damaging liquids (acids or alkalies) in the soil and atmosphere, a metallic sheath of lead or aluminium is provided over the insulation as shown in Figure.



Construction of Cables

- ***Bedding:*** Over the metallic sheath is applied a layer of bedding which consists of a fibrous material like jute or hessian tape. The purpose of bedding is to protect the metallic sheath against corrosion and from mechanical injury due to armoring.
- ***Armoring:*** Over the bedding, armoring is provided which consists of one or two layers of
galvanized steel wire or steel tape. Its purpose is to protect the cable from mechanical injury while laying it and during the course of handling. Armoring may not be done in the case of some cables.
- ***Serving:*** In order to protect armoring from atmospheric conditions, a layer of fibrous material (like jute) similar to bedding is provided over the armoring. This is known as *serving.*

Note: Bedding, armoring and serving are only applied to the cables for the protection of conductor insulation and to protect the metallic sheath from mechanical injury.



Types of Insulating Materials

- The satisfactory operation of a cable depends to a great extent upon the characteristics of insulation used. Therefore, the proper choice of insulating material for cables is of considerable importance.
- In general, the insulating materials used in cables should have the following properties:
  - High insulation resistance to avoid leakage current.
  - High dielectric strength to avoid electrical breakdown of the cable.
  - High mechanical strength to withstand the mechanical handling of cables.
  - Non-hygroscopic *i.e.,* it should not absorb moisture from air or soil. The moisture tends to decrease the insulation resistance and hastens the breakdown of the cable. In case the insulating material is hygroscopic,
it must be enclosed in a waterproof covering like lead sheath.
  - Non-inflammable.
  - Low cost so as to make the underground system a viable proposition.
  - Unaffected by acids and alkalies to avoid any chemical action.

Types of Insulating Materials

- No insulating material possesses all the above mentioned properties.
- Therefore, the type of insulating material to be used depends upon the purpose for which the cable is required and the quality of insulation to be aimed at.
- The principal insulating materials used in cables are:
  - Rubber,
  - Vulcanized India rubber,
  - Impregnated paper,
  - Varnished cambric and
  - Polyvinyl chloride.

Types of Insulating Materials

- **Rubber:** Rubber may be obtained from milky sap of tropical trees or it may be produced from oil products.
- It has relative permittivity varying between 2 and 3, dielectric strength is about 30 kV/mm and resistivity of insulation is 10^{17} Ω cm.
- Although pure rubber has reasonably high insulating properties, it suffers form some major drawbacks:
  - readily absorbs moisture,
  - maximum safe temperature is low (about 38^0C),
  - soft and liable to damage due to rough handling and
  - ages when exposed to light.
- Therefore, pure rubber cannot be used as an insulating material.

Types of Insulating Materials

- **Vulcanized India rubber (V.I.R):** It is prepared by mixing pure rubber with mineral matter such as zine oxide, red lead etc., and 3 to 5% of Sulphur.
- Vulcanization: The compound so formed is rolled into thin sheets and cut into strips. The rubber compound is then applied to the conductor and is heated to a temperature of about 150ºC. The whole process is called *vulcanization* and the product obtained is known as vulcanized India rubber.
- Vulcanized India rubber has greater mechanical strength, durability and wear resistant property than pure rubber.
- Its main drawback is that Sulphur reacts very quickly with copper and for this reason, cables using *VIR* insulation have tinned copper conductor.
- The *VIR* insulation is generally used for low and moderate voltage cables

Types of Insulating Materials

- **Impregnated Paper:** It consists of chemically pulped paper made from wood chippings and impregnated with some compound such as paraffinic or naphthenic material.
- This type of insulation has almost superseded the rubber insulation.
- It is because it has the advantages of low cost, low capacitance, high dielectric strength and high insulation resistance.
- The only disadvantage is that paper is hygroscopic and even if it is impregnated with suitable compound, it absorbs moisture and thus lowers the insulation resistance of the cable.

Types of Insulating Materials

Impregnated Paper (cont.…):

- For this reason, paper insulated cables are always provided with some protective covering and are never left unsealed.
- If it is required to be left unused on the site during laying, its ends are temporarily covered with wax or tar.
- Since the paper insulated cables have the tendency to absorb moisture, they are used where the cable route has a few joints.
- For instance, they can be profitably used for distribution at low voltages in congested areas where the joints are generally provided only at the terminal apparatus.
- However, for smaller installations, where the lengths are small and joints are required at a number of places, *VIR* cables will be cheaper and durable than paper insulated cables.

Types of Insulating Materials

- **Varnished Cambric:** It is a cotton cloth impregnated and coated with varnish.
- This type of insulation is also known as *empire tape.*
- The cambric is lapped on to the conductor in the form of a tape and its surfaces are coated with petroleum jelly compound to allow for the sliding of one turn over another as the cable is bent.
- As the varnished cambric is hygroscopic, therefore, such cables are always provided with metallic sheath.
- Its dielectric strength is about 4 kV/mm and permittivity is 2.5 to 3.8.

Types of Insulating Materials

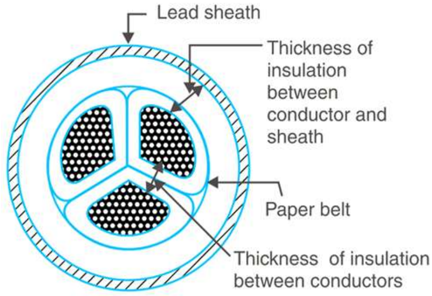
- **Polyvinyl Chloride (PVC):** This insulating material is a synthetic compound. It is obtained from the polymerization of acetylene and is in the form of white powder.
- For a cable insulation, it is compounded with certain materials known as plasticizers which are liquids with high boiling point. The plasticizer forms a gel and renders the material plastic over the desired range of temperature.
- Polyvinyl chloride has high insulation resistance, good dielectric strength and mechanical toughness over a wide range of temperatures. It is inert to oxygen and almost inert to many alkalis and acids.
- Therefore, this type of insulation is preferred over *VIR* in extreme environmental conditions such as in cement factory or chemical factory.
- As the mechanical properties (*i.e.,* elasticity etc.) of *PVC* are not so good as those of rubber, therefore, *PVC* insulated cables are generally used for low and medium domestic lights and power installations.

Cables for 3-Phase Service

- In practice, underground cables are generally required to deliver 3-phase power. For the purpose, either three-core cable or three single core cables may be used. For voltages up to 66 kV, 3-core cable (*i.e.,* multi-core construction) is preferred due to economic reasons. However, for voltages beyond 66 kV, 3-core-cables become too large and unwieldy and, therefore, single-core cables are used.
- The following types of cables are generally used for 3-phase service:
  - Belted cables — up to 11 kV
  - Screened cables — from 22 kV to 66 kV
  - Pressure cables — beyond 66 kV.

Cables for 3-Phase: Belted Cables

- These cables are used for voltages up to 11kV but in extraordinary cases, their use may be extended up to 22kV. The constructional details of a 3-core belted cable is in Figure.
- The cores are insulated from each other by layers of impregnated paper. Another layer of impregnated paper tape, called *paper belt* is wound round the grouped insulated cores. The gap between the insulated cores is filled with fibrous insulating material (jute etc.) so as to give circular cross-section to the cable.
- The cores are generally stranded and may be of noncircular shape to make better use of available space. The belt is covered with lead sheath to protect the cable against ingress of moisture and mechanical injury. The lead sheath is covered with one or more layers of armoring with an outer serving (not shown in the figure)



Cables for 3-Phase: Belted Cables

- The belted type construction is suitable only for low and medium voltages as the electrostatic stresses developed in the cables for these voltages are more or less radial *i.e.,* across the insulation.
- However, for high voltages (beyond 22 kV), the tangential stresses also become important. These stresses act along the layers of paper insulation.
- As the insulation resistance of paper is quite small along the layers, therefore, tangential stresses set up leakage current along the layers of paper insulation.
- The leakage current causes local heating, resulting in the risk of breakdown of insulation at any moment.
- In order to overcome this difficulty, *screened cables* are used where leakage currents are conducted to earth through metallic screens.

Cables for 3-Phase: Screened Cables

These cables are meant for use up to 33 kV, but in particular cases their use may be extended to operating voltages up to 66 kV.

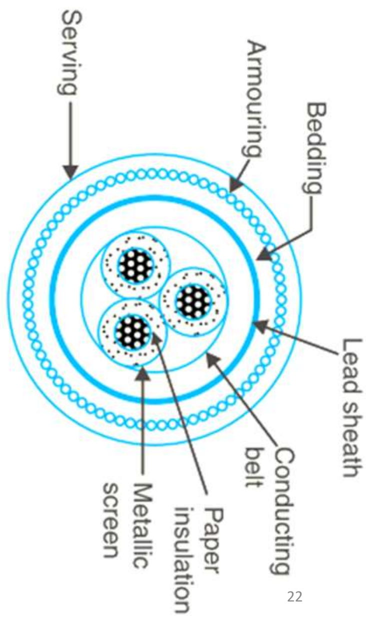
Two principal types of screened cables are:

1. H-type cables and
2. S.L. type cables.

Cables for 3-Phase: Screened Cables

1. **H-type cables**: This type of cable was first designed by "H. Hochstadter" and hence the name. Figure shows the constructional details of a typical 3-core, *H*-type cable.

- Each core is insulated by layers of impregnated paper.
- The insulation on each core is covered with a metallic screen which usually consists of a perforated aluminum foil.
- The cores are laid in such a way that metallic screens make contact with one another.
- An additional conducting belt (copper woven fabric tape) is wrapped round the three cores.
- The cable has no insulating belt but lead sheath, bedding, armoring and serving follow as usual.



Cables for 3-Phase: Screened Cables

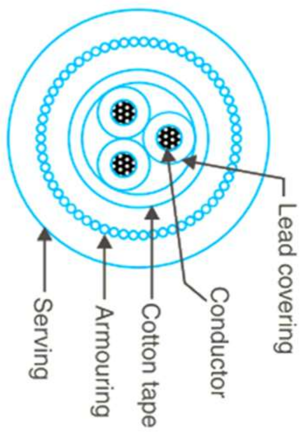
1. H-type cables: …

- It is easy to see that each core screen is in electrical contact with the conducting belt and the lead sheath.
- As all the four screens (3 core screens and one conducting belt) and the lead sheath are at earth potential, therefore, the electrical stresses are purely radial and consequently dielectric losses are reduced.
- ***Two principal advantages***: **(i)** the gaps in the metallic screens assist in the complete impregnation of the cable with the compound and thus the possibility of air pockets or voids (vacuous spaces) in the dielectric is eliminated. The voids if present tend to reduce the breakdown strength of the cable and may cause considerable damage to the paper insulation. **(ii)** the metallic screens increase the heat dissipating power of the cable.

Cables for 3-Phase: Screened Cables

2. S.L. type cables: Figure shows the constructional details of a 3-core S.L. (separate lead) type cable.

- It is basically *H*-type cable but the screen round each core insulation is covered by its own lead sheath. There is no overall lead sheath but only armoring and serving are provided.
- Advantages over *H*-type cables: (i) the separate sheaths minimize the possibility of core-to-core breakdown. (ii) bending of cables becomes easy due to the elimination of overall lead sheath.
- Disadvantage: the three lead sheaths of S.L. cable are much thinner than the single sheath of *H*-cable and, therefore, call for greater care in manufacture.



Limitations of Solid Type Cables

Belted and Screened cables are solid type cables because solid insulation is used in the cable sheath. The voltage limit for solid type cables is 66 kV due to the following reasons :

1. In a solid cable due to load current, its conductor temperature increases and the cable insulating compound expands. This may damage the lead sheath.
2. When the load on the cable decreases, the conductor cools and a partial vacuum is formed within the cable sheath. If the pinholes are present in the lead sheath, moist air may be drawn into the cable. The moisture reduces the dielectric strength of insulation and may eventually cause the breakdown of the cable.
3. The voids are formed as a result of the differential expansion and contraction of the sheath and impregnated compound. The void nearest to the conductor are first to breakdown, the chemical and thermal effects of ionization causing permanent damage to the paper insulation.

Cables for 3-Phase: Pressure Cables

For voltages beyond 66 kV, solid type cables are unreliable because there is a danger of breakdown of insulation due to the presence of voids.

When the operating voltages are greater than 66 kV, *pressure cables* are used. In such cables, voids are eliminated by increasing the pressure of compound and for this reason they are called pressure cables.

Two principal types of Pressure cables are:

1. Oil-filled cables and
2. Gas pressure cables.

Cables for 3-Phase: Pressure Cables

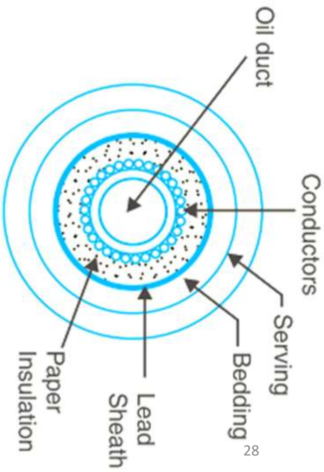
1. Oil-filled cables: In this type of cables, channels or ducts are provided in the cable for oil circulation.

- The oil under pressure (same oil for impregnation) constantly supplied to the channel by means of external reservoirs placed at suitable distances along the route of the cable.
- Oil under pressure compresses the layers of paper insulation and is forced into any voids that may have formed between the layers.
- Due to the elimination of voids, oil-filled cables can be used for higher voltages, the range being from 66 kV up to 230 kV.
- Oil-filled cables are of three types: ***(i)*** single-core conductor channel,
  (ii) single-core sheath channel and
  (iii) three-core filler-space channels.

Cables for 3-Phase: Pressure Cables

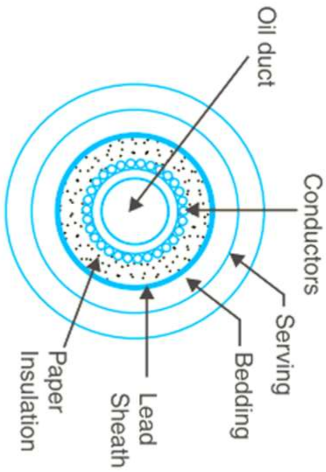
i. single-core conductor channel: Figure shows the constructional details.

- The oil channel is formed at the center by stranding the conductor wire around a hollow cylindrical steel spiral tape.
- The oil under pressure is supplied to the channel by means of external reservoir.
- As the channel is made of spiral steel tape, it allows the oil to percolate between copper strands to the wrapped insulation. The oil pressure compresses the layers of paper insulation and prevents the possibility of void formation.
- The system is so designed that when the oil gets expanded due to increase in cable temperature, the extra oil collects in the reservoir.



Cables for 3-Phase: Pressure Cables

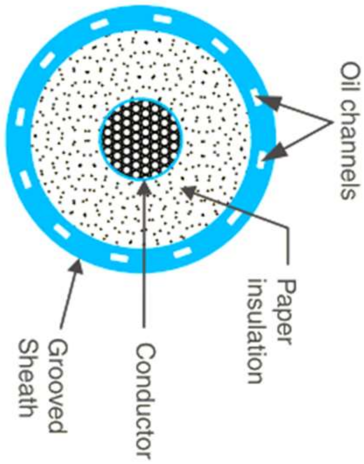
- However, when the cable temperature falls during light load conditions, the oil from the reservoir flows to the channel.
- **The disadvantage** of this type of cable is that the channel is at the middle of the cable and is at full voltage *w.r.t.* earth, so that a very complicated system of joints is necessary



Cables for 3-Phase: Pressure Cables

ii. single-core sheath channel: Figure shows the constructional details.

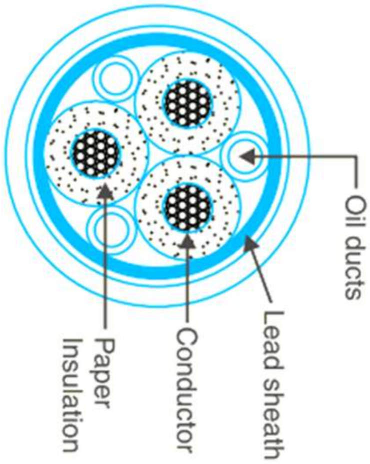
- In this type of cable, the conductor is solid similar to that of solid cable and is paper insulated.
- However, oil ducts are provided in the metallic sheath as shown. In the 3-core oil-filler cable shown



Cables for 3-Phase: Pressure Cables

iii. Three-core oil filler cable: In the 3-core oil-filler cable shown Figure.

- The oil ducts are located in the filler spaces.
- These channels are composed of perforated metal-ribbon tubing and are at earth potential.



Cables for 3-Phase: Pressure Cables

The oil-filled cables have three principal advantages:

1. Formation of voids and ionization are avoided.
2. Allowable temperature range and dielectric strength are increased.
3. If there is leakage, the defect in the lead sheath is at once indicated and the possibility of earth faults is decreased.

The major disadvantages:

1. High initial cost and
2. complicated system of laying.

Cables for 3-Phase: Pressure Cables

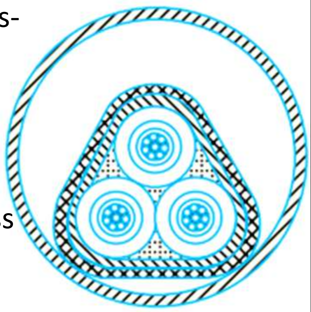
2. Gas pressure cables:

- The voltage required to set up ionization inside a void increases as the pressure is increased.
- Therefore, if ordinary cable is subjected to a sufficiently high pressure, the ionization can be altogether eliminated.
- At the same time, the increased pressure produces radial compression which tends to close any voids. This is the underlying principle of gas pressure cables.

Cables for 3-Phase: Pressure Cables

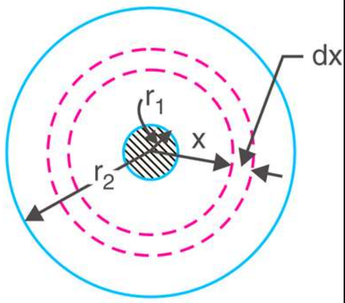
2. Gas pressure cables:

- The construction of the cable is similar to that of an ordinary solid type except that it is of triangular shape and thickness of lead sheath is 75% that of solid cable.
- The triangular section reduces the weight and gives low thermal resistance but the main reason for triangular shape is that the lead sheath acts as a pressure membrane.
- The sheath is protected by a thin metal tape. The cable is laid in a gas-tight steel pipe filled with dry nitrogen gas at 12 to 15 atp.
- The gas pressure produces radial compression and closes the voids between the layers of paper insulation.
- **Advantages:** Carry more load current, operate at higher voltages, less maintenance cost and nitrogen gas helps in quenching any flame.
- **Disadvantage:** the overall cost is very high.



Insulation Resistance

- The cable conductor is provided with a suitable thickness of insulating material in order to prevent leakage current.
- The path for leakage current is radial through the insulation.
- The opposition offered by insulation to leakage current is known as
insulation resistance of the cable.
- For satisfactory operation, the insulation resistance of the cable should be very high.



Insulation Resistance

Consider a single-core cable of conductor radius r_1 and internal sheath radius r_2.

Let *l* be the length of the cable and ρ be the resistivity of the insulation.

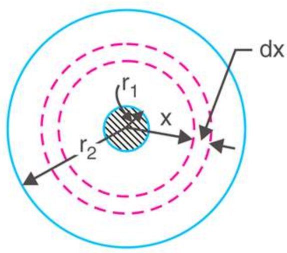
Consider a very small layer of insulation of thickness *dx* at a radius *x*.

The length through which leakage current tends to flow is *dx* and the area of cross-section offered to this flow is 2π *x l*. Therefore, insulation resistance of considered layer

$$= \rho \frac{dx}{2\pi x l}$$

Insulation resistance of the whole cable is

$$R = \int_{r_2}^{r_1} \rho \frac{dx}{2\pi x l} = \frac{\rho}{2\pi l} \int_{r_2}^{r_1} \frac{1}{x} dx = \frac{\rho}{2\pi l} \log_e \frac{r_2}{r_1}$$



This shows that insulation resistance of a cable is inversely proportional to its length.

Insulation Resistance: Numerical-1

A single-core cable has a conductor diameter of 1cm and insulation thickness of 0·4 cm. If the specific resistance of insulation is 5 × 10^{14} Ω-cm, calculate the insulation resistance for a 2 km length of the cable.

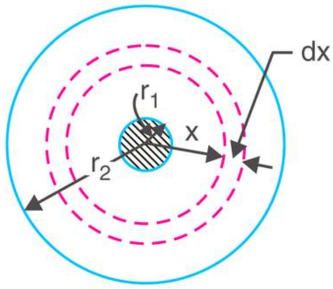
Solution:

Conductor radius $r_1 = ½ = 0.5$ *cm*

Length of Cable l = 2 km = 2000 m

Resistivity of insulation $\rho = 5 \times 10^{14}$ *Ω-cm* $= 5 \times 10^{12}$ *Ω-m*

Internal sheath radius $r_2 = 0.5+0.4 = 0.9$ *cm*



Insulation resistance of cable is

$$R = \frac{\rho}{2\pi l}\log_e\frac{r_2}{r_1} = \frac{5\times10^{12}}{2\pi\times2000}\log_e\frac{0.9}{0.5} = 0.234\times10^9\Omega = 234\ M\Omega$$

Insulation Resistance: Numerical-2

The insulation resistance of a single-core cable is 495 MΩ per km. If the core diameter is 2·5 cm and resistivity of insulation is 4·5 × 10^{14} Ω-cm, find the insulation thickness.

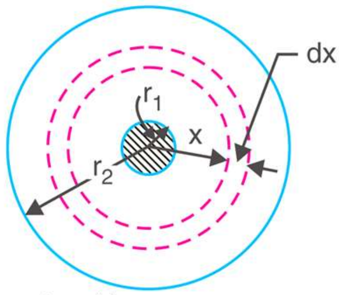
Conductor radius $r_1 = 2.5/2 = 1.25$ *cm*

Cable insulation resistance R = 495 M Ω = 495 X 10^6 Ω

Length of cable l = 1 km = 1000 m

Resistivity of insulation $\rho = 4.5 \times 10^{14}$ *Ω-cm* $= 4.5 \times 10^{12}$ *Ω-m*

Let r_2 *be the internal sheath radius*



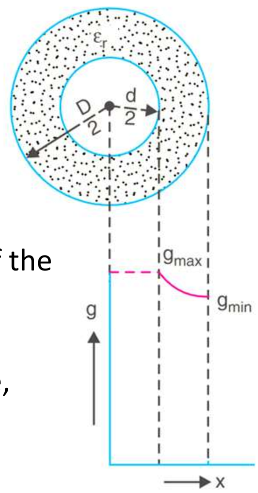
Insulation resistance of cable is $R = \frac{\rho}{2\pi l}\log_e\frac{r_2}{r_1} \rightarrow\rightarrow\rightarrow 495\times10^{12} = \frac{4.5\times10^{12}}{2\pi\times1000}\log_e\frac{r_2}{r_1}$

$$\log_e\frac{r_2}{r_1} = 0.3 \rightarrow\rightarrow\rightarrow \frac{r_2}{r_1} = antilog\ 0.3 = 2$$

Solving for r_2 gives **1.25 cm**

Dielectric Stress in Single-Core Cable

- Under operating conditions, the insulation of a cable is subjected to electrostatic forces.
- This is known as dielectric stress.
- The dielectric stress at any point in a cable is the potential gradient (or electric intensity) at that point.
- Consider a single core cable with core diameter *d* and internal sheath diameter *D.* The electric intensity at a point *x* meters from the center of the cable is $E_x = \frac{Q}{2\pi\varepsilon_0\varepsilon_r x} volts/m$
- By definition, electric intensity is equal to potential gradient. Therefore, potential gradient *g* at a point *x* meters from the center of cable is



$$g = E_x = \frac{Q}{2\pi\varepsilon_0\varepsilon_r x} volts/m \quad \dots\dots\dots\dots (i)$$

Dielectric Stress in Single-Core Cable

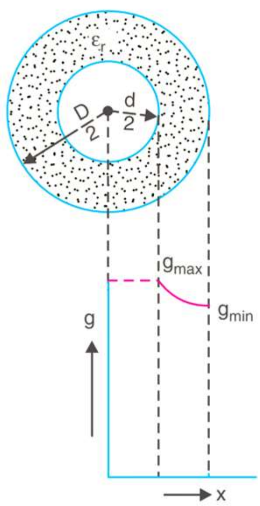
- potential difference *V* between conductor and sheath is

$$V = \frac{Q}{2\pi\varepsilon_0\varepsilon_r}\log_e\frac{D}{d}\ volts\ (or)\ Q = \frac{2\pi\varepsilon_0\varepsilon_r V}{\log_e\frac{D}{d}} \quad \dots\dots\dots\dots (ii)$$

- Substituting the value of *Q* from exp. (*ii*) in exp. (*i*), we get,

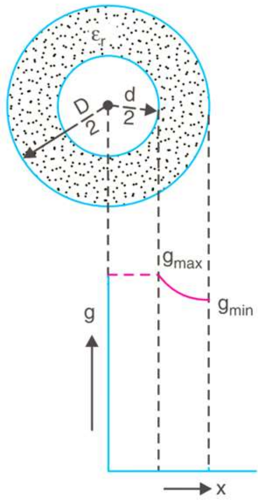
$$g = E_x = \frac{2\pi\varepsilon_0\varepsilon_r V \Big/ \log_e D/d}{2\pi\varepsilon_0\varepsilon_r}$$

$$g = \frac{V}{x\log_e D/d} volts/m \dots\dots\dots \quad (iii)$$



Dielectric Stress in Single-Core Cable

- It is clear from exp. (*iii*) that potential gradient varies inversely as the distance *x.* Therefore, potential gradient will be maximum when *x* is minimum *i.e.,* when *x* = *d*/2 or at the surface of the conductor. On the other hand, potential gradient will be minimum at *x* = *D*/2 or at sheath surface.



- Maximum potential gradient is

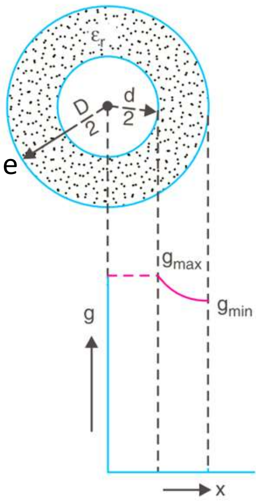
$$g_{max} = \frac{2V}{d \log_e D/d} \, volts/m \ldots\ldots\ldots \quad [substituting\ x = \frac{d}{2}\ in\ (iii)]$$

- Minimum potential gradient is

$$g_{min} = \frac{2V}{D \log_e D/d} \, volts/m \ldots\ldots\ldots \quad [substituting\ x = \frac{D}{2}\ in\ (iii)]$$

Dielectric Stress in Single-Core Cable

- The variation of stress in the dielectric is shown in Figure. It is clear that dielectric stress is maximum at the conductor surface and its value goes on decreasing as we move away from the conductor.
- It may be noted that maximum stress is an important consideration in the design of a cable.
- For instance, if a cable is to be operated at such a voltage that maximum stress is 5 kV/mm, then the insulation used must have a dielectric strength of at least 5 kV/mm, otherwise breakdown of the cable will become inevitable.



$$\frac{g_{max}}{g_{min}} = \frac{\dfrac{2V}{d \log_e D/d}}{\dfrac{2V}{D \log_e D/d}} = \frac{D}{2}$$

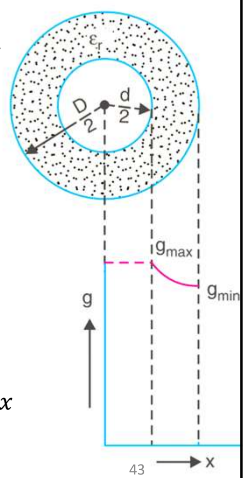
Dielectric Stress: Numerical-1

A 33 kV single core cable has a conductor diameter of 1 cm and a sheath of inside diameter 4 cm. Find the maximum and minimum stress in the insulation.

V = 33 kV (r.m.s.); d = 1 cm; D = 4 cm

The maximum stress occurs at the conductor surface and its value is given by

$$g_{max} = \frac{2V}{d \log_e {}^{D}/_{d}} = \frac{2 \times 33}{1 \ \log_e {}^{4}/_{1}} {}^{KV}/_{cm} = 47.61 \ {}^{kV}/_{cm} \ (r.m.s.)$$



Minimum potential gradient is

$$g_{min} = \frac{2V}{D \log_e {}^{D}/_{d}} = \frac{2 \times 33}{4 \ \log_e {}^{4}/_{1}} {}^{KV}/_{cm} = 11.9 \, {}^{kV}/_{cm} \, (r.m.s.)$$

Alternatively , using the relationship $\frac{g_{max}}{g_{min}} = \frac{D}{d}$ →→→ $g_{min} = \frac{d}{D} \times g_{max}$

Dielectric Stress: Numerical-2

The maximum and minimum stresses in the dielectric of a single core cable are 40 kV/cm (r.m.s.) and 10 kV/cm (r.m.s.) respectively. If the conductor diameter is 2 cm,

find : (i) thickness of insulation (ii) operating voltage

Given g_{max} = 40 kV/cm; g_{min} = 10 kV/cm; d = 1 cm; D = ?

(i) Using the relationship $\frac{g_{max}}{g_{min}} = \frac{D}{d}$ →→→ $D = \frac{g_{max}}{g_{min}} \times d = \frac{40}{10} \times 2 = 8 \ cm$

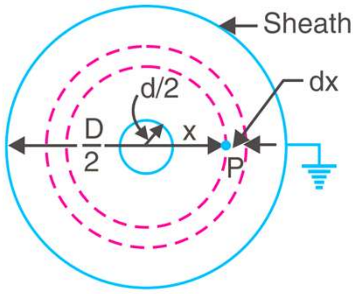
∴ Insulation thickness $= \frac{D-d}{2} = \frac{8-2}{2} = 3 \ cm$

(ii) $g_{max} = \frac{2V}{d \log_e {}^{D}/_{d}}$ →→→ $V = \frac{g_{max} \times d \log_e {}^{D}/_{d}}{2}$

$$V = \frac{40 \ \times 2 \log_e {}^{4}/_{1}}{2} = 55.45 \ kV (r.m.s.)$$

Capacitance of a Single-Core Cable

- A single-core cable can be considered to be equivalent to two long co-axial cylinders.
- The conductor (or core) of the cable is the inner cylinder while the outer cylinder is represented by lead sheath which is at earth potential.
  Consider a single core cable with conductor diameter *d* and inner sheath diameter *D*.
- Let the charge per meter axial length of the cable be *Q* coulombs and ε be the permittivity of the insulation material between core and lead sheath. ($\varepsilon = \varepsilon_0 \varepsilon_r$)



Capacitance of a Single-Core Cable

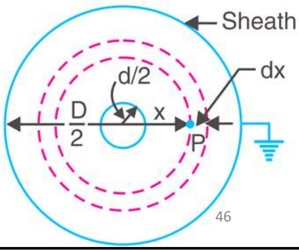
Consider a cylinder of radius *x* meters and axial length 1 meter. The surface area of this cylinder is = 2 π *x* × 1 = 2 π *x* m^2

Electric flux density at any point *P* on the considered cylinder is $D_x = \frac{Q}{2\pi x} C/_{m^2}$

Electric intensity at point P, $E_x = \frac{D_x}{\varepsilon} = \frac{Q}{2\pi x \varepsilon} = \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} volts/_m$

The work done in moving a unit positive charge from point *P* through a distance *dx* in the direction of electric field is $E_x dx$. Hence, the work done in moving a unit positive charge from conductor to sheath, which is the potential difference *V* between conductor and sheath, is given by :

$$V = \int_{d/_2}^{D/_2} E_x dx = \int_{d/_2}^{D/_2} \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} dx = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \log_e \frac{D}{d}$$



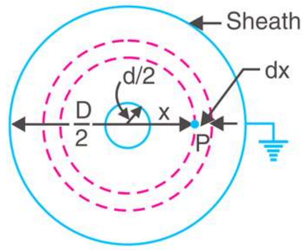
Capacitance of a Single-Core Cable

Capacitance of the cable is:

$$C = \frac{Q}{V} = \frac{Q}{\frac{Q}{2\pi\varepsilon_0\varepsilon_r}\log_e\frac{D}{d}} = \frac{2\pi\varepsilon_0\varepsilon_r}{\log_e\frac{D}{d}} F/m$$

$$= \frac{2\pi \times 8.854 \times 10^{-12} \times \varepsilon_r}{2.303\log_e\frac{D}{d}} F/m$$

$$= \frac{\varepsilon_r}{41.4\log_e\frac{D}{d}} \times 10^{-9}\, F/m$$



If the cable has a length of l meters, then the capacitance of the cable is:

$$C = \frac{\varepsilon_r \times l}{41.4\log_e\frac{D}{d}} \times 10^{-9} F$$

Capacitance of Cable: Numerical-1

A single core cable has a conductor diameter of 1 cm and internal sheath diameter of 1·8 cm. If impregnated paper of relative permittivity 4 is used as the insulation, calculate the capacitance for 1 km length of the cable.

Given data: $\varepsilon_r = 4$ $l = 1000\ m$ $D = 1.8\ cm$ $d = 1\ cm$

Capacitance of the cable is: $C = \frac{\varepsilon_r \times l}{41.4\log_e\frac{D}{d}} \times 10^{-9}F$

$$C = \frac{4\times1000}{41.4\log_e\frac{1.8}{1}} \times 10^{-9}F = 0.378 \times 10^{-6}F = 0.378\ \mu F$$

Capacitance of Cable: Numerical-2

Calculate the capacitance and charging current of a single core cable used on a 3-phase, 66 kV system. The cable is 1 km long having a core diameter of 10 cm and an impregnated paper insulation of thickness 7 cm. The relative permittivity of the insulation may be taken as 4 and the supply at 50 Hz.

Given data: $\varepsilon_r = 4$ $l = 1000\ m$ $d = 10\ cm$ $D = 10 + 2x7 = 24\ cm$

Capacitance is: $C = \frac{4 \times 1000}{41.4 \log_e \frac{24}{10}} \times 10^{-9} F = 0.254 \times 10^{-6} F = 0.254\ \mu F$

Voltage between core and sheath is $V_{ph} = {}^{66}/_{\sqrt{3}} = 38.1\ kV$

Charging current $= {}^{V_{ph}}/_{X_C} = 2\pi f C V_{ph}$

$= 2\pi \times 50 \times 0.254 \times 10^{-6} \times 38.1 \times 10^{-3} = 3.04\ A$

Capacitance of a Three-Core Cable

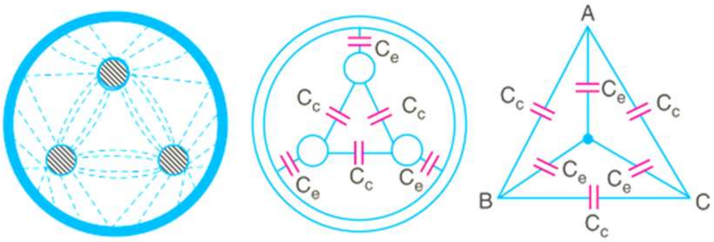
The capacitance of a cable system is much more important than that of overhead line because in cables

1. conductors are nearer to each other and to the earthed sheath
2. they are separated by a dielectric of permittivity much greater than that of air.

Capacitance of a Three-Core Cable

1. Since potential difference exists between pairs of conductors and between each conductor and the sheath, electrostatic fields are set up in the cable as shown in Fig.(*i*).
2. These electrostatic fields give rise to core-core capacitances *Cc* and conductor-earth capacitances *Ce* as shown in Fig. (*ii*).
3. The three *Cc* are delta connected whereas the three *C e* are star connected, the sheath forming the star point as shown in Fig. (*iii*).

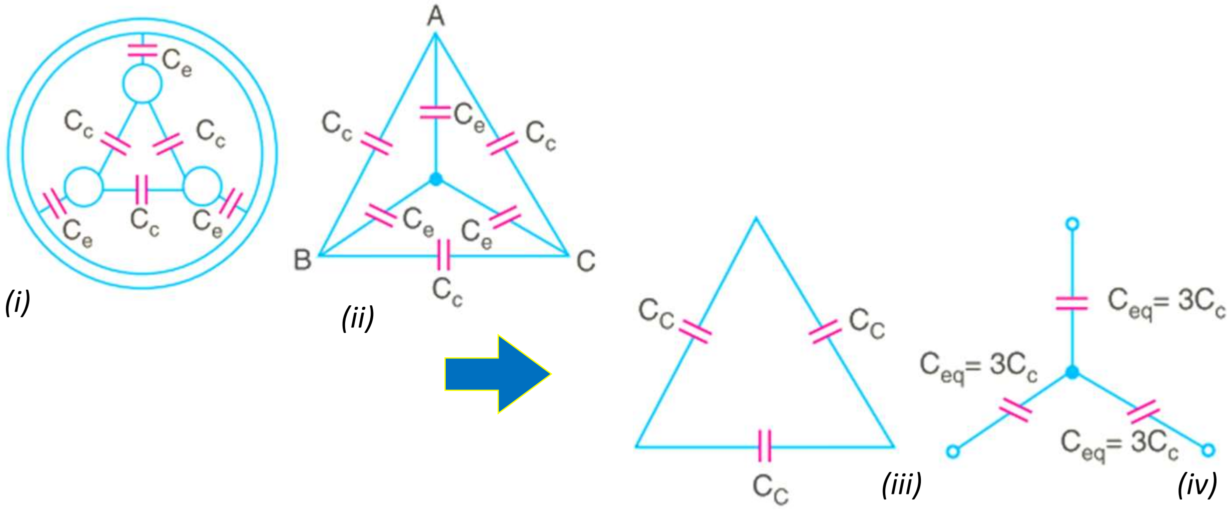
Figure: A system of capacitances in a 3-core belted cable used for 3-phase system



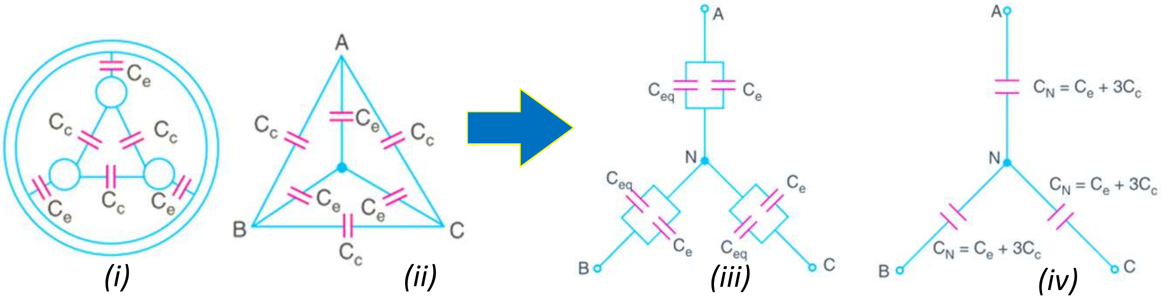
(*i*) (*ii*) (*iii*)

Capacitance of a Three-Core Cable

- Converting into equivalent delta or star connected capacitance



Capacitance of a Three-Core Cable



- The system of capacitance shown in (ii) can be reduced to equivalent circuit shown in (iii).
- Therefore, the whole cable is equivalent to three star-connected capacitor each of capacitance as shown in Fig. (iv). $C_N = C_e + C_{eq} = C_e + 3C_c$
- If V_{ph} is the phase voltage, then charging current I_C is given by:
- $I_c = \frac{V_{ph}}{Capacitive\ reactance\ per\ phase} = 2\pi f V_{ph} C_N = 2\pi f V_{ph}(C_e + 3C_c)$

Measurement of C_e and C_c

1. Although core-core capacitance *Cc* and core-earth capacitance *Ce* can be obtained from the empirical formulas for belted cables, their values can also be determined by measurements. For this purpose, the following two measurements are required
   1. In the first measurement, the three cores are bunched together and the capacitance is measured between the bunched cores and the sheath. The bunching eliminates all the three capacitors C_c, leaving the three capacitors *Ce* in parallel. Therefore, if C_1 is the measured capacitance, this test yields : $\boldsymbol{C_1 = 3C_e}$
   2. In the second measurement, two cores are bunched with the sheath and capacitance is measured between them and the third core. This test yields $2C_c + C_e$. If C_2 is the measured capacitance, then $\boldsymbol{C_2 = 2C_c + C_e}$

As the value of C_e is known from first test and C_2 is found experimentally, therefore, value of C_c can be determined.

Measurement of C_e and C_c

- It may be noted here that if value of C_N is desired, it can be found directly by another test.
- In this test, the capacitance between two cores or lines is measured with the third core free or connected to the sheath.
- This eliminates one of the capacitors C_e so that if C_3 is the measured capacitance, then,

$$C_3 = C_c + \frac{C_c}{2} + \frac{C_e}{2}$$
$$= \frac{1}{2}(C_e + 3C_c)$$
$$= \frac{1}{2}C_N$$

Capacitance of Cable: Numerical

The capacitances of a 3-phase belted cable are 12·6 μF between the three cores bunched together and the lead sheath and 7·4 μF between one core and the other two connected to sheath. Find the charging current drawn by the cable when connected to 66 kV, 50 Hz supply.

$$V_{ph} = \frac{66 \times 10^3}{\sqrt{3}} = 38105\, V; f = 50\, Hz;\ C_1 = 12.6\, \mu F;\ C_2 = 7.4 \mu F$$

Let core-to-core and core-to-earth capacitance of the cable be C_c and C_e respectively.

$$C_1 = 3C_e \to\to\to 3C_e = {}^{C_1}/_3 = {}^{12.6}/_3 = 4.2\ \mu F$$

And $C_2 = 2C_c + C_e \to\to\to C_c = \frac{C_2 - C_e}{2} = \frac{7.4-4.2}{2} = 1.6\ \mu F$

Core to neutral capacitance is $C_N = C_e + 3C_c = 4.2 + 3 \times 1.6 = 9\ \mu F$

Charging current $I_c = 2\pi f V_{ph} C_N = 2\pi \times 50 \times 38105 \times 9 \times 10^{-6} A = 107.74\ A$